$3.00

ATOMIC RADIATION DETECTION AND MEASUREMENT

by HAROLD S. RENNE

Editorial Staff

LLOYD J. AUSTIN • DONALD E. HERRINGTON • FRED McKINNEY, JR.

FIRST EDITION—FIRST PRINTING

JULY, 1955

ADR-1

Published by

HOWARD W. SAMS & CO., INC., INDIANAPOLIS 5, INDIANA

A Howard W. Sams PHOTOFACT PUBLICATION

LITHO IN U.S.A.

Library of Congress Catalog Card Number: 55 — 10222

FOREWORD

Interest in nuclear science and its application is expanding at a tremendous rate, and this rate of expansion shows promise of being accelerated still further as time goes on. Nuclear reactors are being built in ever-increasing numbers, atomic power plants are in the advanced planning stage, at least one nuclear-powered submarine is in operation, and new applications of radioactive isotopes are being discovered daily.

A great deal of information on nuclear science is available, but for the most part is widely scattered. It was felt that there was a need for a book which would collect together within its covers all the information necessary for a basic understanding of nuclear science and its applications, and more particularly for an understanding of the equipment and techniques required for detecting and measuring atomic radiation. This book is an attempt to meet that need.

To be of interest and value to a maximum number of readers, this volume has been written so that anyone who has had the equivalent of a good course in general science at the high school or first year college level can understand the majority of the material. For the chapters in which electronic circuits are presented, some knowledge of circuitry is desirable but not essential.

The book is divided into three basic sections. Chapters 1, 2, and 3 include a general discussion of nuclear theory, atomic reactions, and radiation and its effects. The next four chapters describe in considerable detail a few of the many types of instruments used to detect and measure atomic radiation, such as Geiger counters, scintillation counters, and dosimeters. Construction details on typical instruments are included for the experimenter. Chapters 8, 9, and 10 will give the reader a general idea of some of the applications of nuclear science, and how radiation detection and measuring equipment is employed in industry, civil defense, and prospecting.

To further increase the usefulness of this book, several appendices have been added, including a manufacturer's directory, product directory, glossary of abbreviations and terms peculiar to nuclear science, and a fairly extensive bibliography for those who wish to read further.

In any undertaking of this nature, a great deal of help and cooperation is essential. Such help has been given me unstintingly. My sincere thanks is hereby extended to the many manufacturers who provided technical details on their products, to the magazines whose editors kindly gave permission to reproduce material which they had published, to the Atomic Energy Commission, the National Bureau of Standards, and the Civil Defense organizations. Many thanks also to the staff of Radio & Television News for their help and guidance, and in particular to Mr. Oliver Read, editor and assistant to the publisher, without whose inspiration and kind words of encouragement this book would not have been written.

Harold S. Renne

TABLE OF CONTENTS

CHAPTER		PAGE
1.	Atomic Structure	7
2.	Atomic Radiation and Its Effects	15
3.	Radiation Detection Devices	25
4.	Commercial Geiger Counters	41
5.	Scintillation Counters	71
6.	Home-Built Counters	89
7.	Dosimeters	117
8.	Applications of Nuclear Science	135
9.	Civil Defense	157
10.	Prospecting	165

Appendix

I	Manufacturers' Directory	177
II	Product Directory	181
III	Abbreviations	185
IV	Definitions	187
V	Bibliography	193

CHAPTER 1

Atomic Structure

Since the beginning of time, man has been delving into the secrets of nature in an attempt to determine the exact structure of matter. Although a great deal still remains to be learned, many of the secrets have now been uncovered. Progress was particularly rapid following the discovery of atomic fission because of the tremendous efforts put forth by scientists in the United States as well as in other countries. These efforts were stimulated by the search for a workable atomic bomb.

Some knowledge of the findings of nuclear physicists is essential to an understanding of nuclear reactions and atomic radiation. Such knowledge gives us a better insight into the inner workings of atoms and the various atomic building blocks. In this book, we will briefly review presently available information in the nuclear field, and will discuss in some detail the equipment and techniques used in detecting and measuring the radiations resulting from nuclear reactions.

Atomic Building Blocks

If a piece of an element such as iron is cut in two, then cut in two again, and so on, until we have the smallest piece which we could get and still have iron, this piece would be called an atom. Actually carrying out the subdividing process would be extremely difficult, because the atom is so very small. For many years, it was thought that the atom was the smallest particle existing in the universe, but now we know that this is not true.

Atoms are made up of three basic building blocks — electrons, protons, and neutrons, each of which is smaller than the atom itself. The atoms of the various elements differ from each other only in the number and arrangement of these building blocks.

The electron is the smallest and lightest known particle and carries with it a unit charge of negative electricity. When electrical current flows through a wire, or through a vacuum tube, the flow is made up primarily of electrons passing through the wire or through the space between the elements of the vacuum tube.

The proton is much heavier than the electron — about 1840 times as heavy, in fact. It carries a unit charge of positive electricity, equal and opposite to that of the electron. The proton is seldom found outside the nucleus of atoms, except when nuclear reactions of some kind are taking place.

The neutron has a mass the same as that of the proton, but as its name implies, it is electrically neutral. When in motion, it cannot be deflected by either a magnetic or electric field. This made its discovery difficult, and it was not definitely identified until 1932. It appears in many nuclear reactions, and is used extensively for nuclear bombardment.

Scientists have discovered the existence of at least three other particles in various nuclear reactions which should be mentioned in passing. These are the positron, the meson, and the neutrino.

The positron has a mass equivalent to that of the electron, but has a unit positive charge. Its life is extremely short, as it combines with an electron to form energy.

Mesons are elusive particles which may have a positive or negative charge, or no charge at all. They appear in cosmic ray showers, and in the outputs of some of the larger nuclear accelerators. Mesons of several different masses have been discovered, all intermediate between the mass of an electron and the mass of a proton. The life of a meson is very short, making observation of its characteristics difficult.

The neutrino apparently is a particle having the mass of an electron but without any charge whatever. Although we know very little about it, the concept of the neutrino is useful in explaining certain nuclear reactions.

Atomic and Nuclear Structure

In general, the atom is considered to be made up of a very compact core called a nucleus, around which a number of electrons travel in orbits. The nucleus itself is made up of various numbers of protons and neutrons bound together by some force not as yet completely understood. Since the protons are all positively charged, it would be expected that these charges would mutually repel each other and tear the nucleus apart. The nuclear binding force greatly exceeds this force of repulsion, and serves to hold protons and neutrons together very tightly.

The number of electrons traveling in orbits around the nucleus is equal to the number of protons in the nucleus for a normal atom. Thus, in its normal state, the atom is electrically neutral. Normal hydrogen and helium atoms are shown schematically in Fig. 1-1. If one or more of the orbital electrons is removed by some means, the atom is left with a net positive charge, and is said to be ionized. As

we shall see later, this ionization process plays a very important role in our study of nuclear radiation.

Chemical properties of a normal atom are determined by the number of protons in the nucleus (or electrons surrounding the nucleus). This quantity is called the atomic number. Normal hydrogen, the lightest element, has one proton in the nucleus, and one

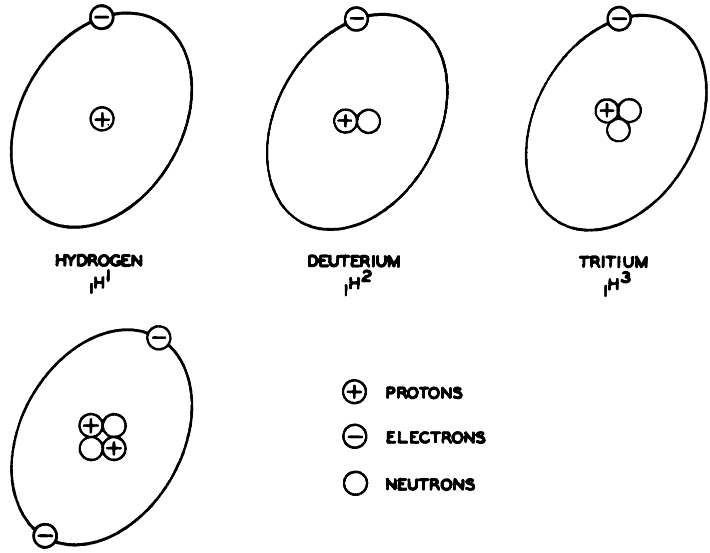


Fig. 1-1. Schematic Representation of a Hydrogen Atom, Two Hydrogen Isotopes, and a Helium Atom.

orbital electron, so it has an atomic number of one. Uranium, one of the largest atoms, has 92 protons in the nucleus and 92 orbital electrons and, therefore, has an atomic number of 92.

Neutrons in the nucleus contribute to the mass of the atom, but have no effect on its chemical properties. As the total mass is important in our discussion, we assign a mass number to the atom which is equal to the sum of the protons and neutrons in the nucleus. Normal boron, whose nucleus contains five protons and five neutrons, has a mass number of 10. Hydrogen, with a single nuclear proton and no neutrons has a mass number of 1.

A shorthand-type of notation has been developed so that the mass number and atomic number of an element can be clearly indicated. The atomic number is written as a subscript at the left of the symbol for the element, and the mass number as a superscript at the right. *

---

* In some notations, both the subscript and the superscript are at the right of the symbol for the element. The meanings are the same. Example: B_5^{10} means the same as $_5B^{10}$.

Thus, boron with a symbol of B, an atomic number of 5 and a mass number of 10, is written $_5B^{10}$. This symbolism is used extensively in nuclear notations, and will be encountered frequently in the following pages. Sometimes, in practice, the atomic number subscript is disregarded. Thus, B^{10} and $_5B^{10}$ both have the same meaning.

The mass number of an element is very nearly equal to its atomic weight, which is the weight in grams of a certain specified number of atoms. However, in most elements, there are slight but important differences.

Isotopes

As the chemical properties of an atom are not affected by the number of neutrons in the nucleus, we might expect to find atoms with the same atomic number as the normal atom, but with a different mass number. Such atoms have been discovered for nearly every element, and are called isotopes. An isotope has the same number of protons in its nucleus as a normal atom, but has either more or fewer neutrons. It is important to note that an isotope cannot be differentiated chemically from the mother element, as the chemical properties of the two are identical. The only way of telling them apart is by the difference in atomic weight.

There are over 280 known stable isotopes, as well as many unstable ones. The number of isotopes per element is distributed very unevenly, being determined by rules that govern the stability of nuclei. The boron isotope, with an atomic weight of 11, has five protons and six neutrons in its nucleus compared with five protons and five neutrons for the normal boron atom, and is written symbolically as $_5B^{11}$. The boron atom and its isotope cannot be distinguished from each other by chemical means.

An isotope which has found extensive use in nuclear reactions is the so-called heavy hydrogen, or deuterium. Normal hydrogen is written symbolically $_1H^1$. Deuterium consists of a normal hydrogen atom whose nucleus has acquired a neutron, giving it a mass number of 2. Deuterium is thus written $_1H^2$. Hydrogen as it occurs in nature contains only a very small proportion of deuterium, but ways have been devised for increasing this concentration, so that nearly pure deuterium is now available. Water made with deuterium is called heavy water. If the hydrogen nucleus acquires two neutrons, which sometimes occurs, we have tritium, or $_1H^3$. A schematic representation of deuterium and tritium are shown in Fig. 1-1.

Normal uranium has 92 protons and 146 neutrons in its nucleus, giving it an atomic number of 92 and a mass number of 238, written as $_{92}U^{238}$. Later on we will be interested in an isotope of uranium containing 3 less neutrons in its nucleus, or $_{92}U^{235}$, which is the so-called "fissionable" uranium used in the first atomic bomb.

Energy and the Electron Volt

In atomic physics, we are continually dealing with energy in one form or another. To reduce energy to a common denominator, the term electron volt (ev) is used. An electron volt is the energy acquired by a unit charge of electricity when the charge moves through a potential difference of one volt. For example, if an electron should start at a potential of zero volts and travel to a point having a potential of 300 volts, it would acquire an energy equivalent to 300 electron volts.

As the charge on an electron is very small, an electron volt of energy is tiny indeed. For example, a 10-watt lamp burning for one second consumes the equivalent of about 62 billion-billion (62×10^{18}) electron volts of energy. A more common term is a million electron volts (mev), a million times larger than the electron volt, and equivalent to the energy acquired by an electron in moving through a potential difference of one million volts, or a million electrons moving through a potential difference of one volt. Even this unit represents a very small amount of energy, being equivalent to about 1.18×10^{-13} foot-pounds, or 4.45×10^{-20} kilowatt-hours. However, as we will be dealing mostly with individual atoms, this unit is very convenient to use. Occasionally, a unit of one thousand electron volts (kev) is encountered.

In early experiments with nuclear reactions, it was found in some cases that mass apparently disappeared — in other words, the end products of the reaction weighed less than the initial products. However, in these cases, energy was also released. Careful measurements served to verify Einstein's theory of the equivalence of mass and energy, which is given by the equation:

$$\text{Energy} = \text{Mass} \times (\text{velocity of light})^2$$

where energy is expressed in ergs, mass in grams, and the velocity of light in centimeters per second.

The velocity of light is approximately 3×10^{10} cm per sec., and this factor squared is 9×10^{20}. Thus, an extremely small amount of mass is equivalent to a tremendous amount of energy. If one pound of matter could be completely converted to energy, it would be equivalent to that produced by burning 1 1/2 million tons of coal. In nuclear reactions, loss of a small amount of mass can result in a large release of energy. One proton or one neutron, for example, is equivalent to 931 mev, and the energy equivalent of an electron is 0. 51 mev.

Nuclear Reactions

Work in nuclear physics is concerned primarily with the disruption and reorganization of atomic nuclei. This disruption can be caused by natural radioactivity, or by firing particles at the nucleus with sufficient energy to cause a reaction of some kind. The particles

which can be fired are electrons, protons, neutrons, and combinations of these. Working with projectiles can be extremely difficult, however, as the atom is practically all empty space, and the nucleus presents a very small target. The diameter of an atom is approximately 10,000 times as great as that of its nucleus. Therefore, the actual volume occupied by the nucleus is only about one trillionth (10^{-12}) that of the whole atom. If all this extra space in atoms could be eliminated, the earth would be only about 4/5 mile in diameter, and matter would weigh about two hundred million tons per cubic inch.

A factor making it difficult to strike the nucleus with a positively charged particle is the potential barrier surrounding it due to the concentrated positive charge it contains. This potential barrier repels a positive charge very strongly. Neutrons are frequently used as projectiles, as the positive charge on the nucleus has no effect on them.

Another factor is also involved. If neutrons are traveling very rapidly, they can pass right through a material without ever striking a nucleus. As brought out before, the atoms of the material are mostly empty space, and the nuclei present very minute targets. In many reactions, it is necessary to slow down the neutrons so that the chances of striking a nucleus are improved. Heavy water, graphite, and paraffin have been used for this purpose.

Let us consider briefly some of the nuclear reactions with which scientists have worked. Such reactions may be represented by equations, using the symbols discussed previously. A typical example will indicate how such equations are used. Firing a neutron into an atom of boron produces a well-known nuclear reaction. The symbol for a neutron is ${}_1n^0$. Thus, on the left side of the equation, we add a neutron to a boron atom:

$${}_5B^{10} + {}_1n^0$$

Reaction products are a lithium atom, an alpha particle (helium nucleus), and some energy, written as:

$${}_3Li^7 + {}_2He^4 + \text{energy}$$

The complete reaction then becomes:

$${}_5B^{10} + {}_1n^0 \rightarrow {}_3Li^7 + {}_2He^4 + \text{energy}$$

In this reaction, the amount of energy released may be used to verify Einstein's equation concerning the equivalence of mass and energy. If we add the atomic weights on the two sides of this equation, we find that they are not equal:

$$10.01605 + 1.00893 = 7.01804 + 4.00389 + \text{energy}$$

The difference is .00305 units of atomic weight, which is equivalent to 2.85 mev. This predicted energy release agrees with the experi-

mentally observed energies of the two nuclei resulting from the reaction.

Another startling fact is revealed by the foregoing reaction. By merely firing a neutron at a boron nucleus, the boron disappears and two completely new elements, helium and lithium, are formed. Thus, we have accomplished the transmutation of elements — a dream of the alchemists of old.

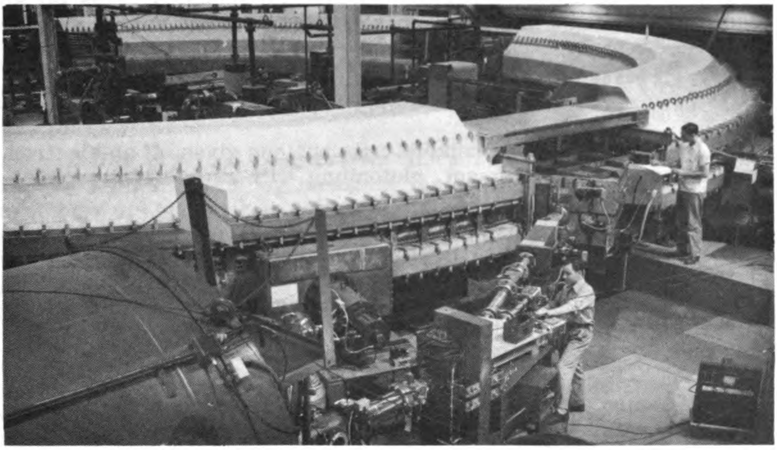


Fig. 1-2. View of the Cosmotron at Brookhaven National Laboratory. Particles with Energies in Excess of Three Billion Electron Volts Have Been Obtained from This Device.

As mentioned before, atomic projectiles can be electrons, protons, alpha particles, or neutrons. The first three particles carry with them an electrical charge, so they can be accelerated and deflected at will by means of electric and magnetic fields. Many devices have been built for accelerating these particles to very high speeds, including the cyclotron, synchrotron, betatron, and others. The accelerator at Brookhaven National Laboratory, called the cosmotron, can produce particles having over three billion electron volts of energy. Fig. 1-2 shows a view of the cosmotron.

Neutrons are extremely useful as projectiles, but are much more difficult to handle than charged particles. They can be formed only as a result of nuclear reactions, and after their formation, they cannot be accelerated. One method of forming them is to fire high-speed alpha particles at beryllium or boron. The resulting second-hand neutrons can then be used to bombard other nuclei.

In 1934, Enrico Fermi tried bombarding various heavy elements with a stream of neutrons. When uranium was used as the target, he discovered that a new element, plutonium, had been produced. The

process is now quite well understood, and is used in making plutonium for atom bombs. Electrons are released in the reaction. The symbol for an electron is ${}_{-1}e^0$.

First, the uranium nucleus captures the neutron to form a uranium isotope:

$$ {}_{92}U^{238} + {}_{1}n^{0} \rightarrow {}_{92}U^{239} $$

This isotope is unstable and the nucleus immediately gives off an electron, forming a new element, neptunium, with an atomic number of 93:

$$ {}_{92}U^{239} \rightarrow {}_{93}Np^{239} + {}_{-1}e^{0} $$

Neptunium is also unstable. Its nucleus gives off an electron, yielding another new element, plutonium, with atomic number 94:

$$ {}_{93}Np^{239} \rightarrow {}_{94}Pu^{239} + {}_{-1}e^{0} $$

Plutonium is relatively stable until bombarded with slow neutrons. It then literally blows itself to pieces, giving a whole series of atoms of smaller atomic weight and releasing vast quantities of energy. This process is known as nuclear fission.

Emission of an electron from the nucleus of an atom requires some explanations which are not as yet completely satisfactory. In our discussion of atomic structure, nothing was said about electrons in the nucleus. The best explanation at present is that one of the neutrons gives off an electron and becomes a proton. Just how this takes place is one of the atomic mysteries still defying solution.

In this book, we are primarily concerned with radioactive materials in which an element breaks down spontaneously to give a new element or elements plus radiation of some kind. Some elements, such as radium and uranium, are naturally radioactive; others can be made artificially radioactive by bombardment with neutrons or other particles. In the next chapter, we will study the various kinds of radiation given off when radioactive materials break down.

CHAPTER 2

Atomic Radiation and its Effects

In the previous chapter, we discussed the possibility of disrupting atomic nuclei by means of various kinds of bullets, such as neutrons or high-speed protons. When such disruptions occur spontaneously without external bombardment, as in radium, we say the element is radioactive. Several elements are naturally radioactive to a greater or lesser degree, and many radioactive isotopes can be formed artificially by neutron bombardment.

Radiation of various kinds is usually given off when atomic nuclei break up spontaneously in the radioactive process. We are concerned in this chapter with the characteristics of this atomic radiation and with some of its effects. In this connection, a ray is considered to be a bundle of particles or energy, such as radio waves.

Atomic Radiation

A study of the rays emitted by radioactive materials reveals that three main types of radiation are involved. These three have been called alpha rays, beta rays, and gamma rays, referred to symbolically by the corresponding Greek letters alpha (α), beta (β), and gamma (γ).

Alpha rays (α) are deflected only slightly by strong electric and magnetic fields, which indicates that they must consist of fairly heavy particles. Measurement of the deflection in known fields, along with other data, gives us enough information to determine the charge and mass of each particle, and we find these characteristics to be the same as those of a helium nucleus. In other words, an alpha particle is made up of two protons and two neutrons, and so has a net positive charge of two and an atomic number of four. It is written as ${}_2He^4$.

The range of alpha particles is limited, as they ionize very heavily and lose their energy rapidly by such ionization. They are unable to penetrate the unbroken skin but if an element liberating them is deposited within the body, severe damage may result. In any specific nuclear reaction, all the alpha particles given off have essentially the same energy, and so the same range.

Beta rays (β) are made up of electrons and are easily deflected by rather weak electric and magnetic fields. Because electrons are so light in weight, they are easily bounced around in any material through which they pass, and their actual range is variable. At most, they will go through about a third of an inch of body tissue. They don't ionize as heavily as alpha particles, but can cause moderate amounts of damage when contacted either externally or internally. Damage to tissues is a direct result of ionization.

Individual beta particles given off in a specific reaction can differ widely in energy content, as contrasted with monoenergetic alpha particles. This difference in energy content contributes to the variable range.

Gamma rays (γ) cannot be deflected by either a magnetic or an electric field. They consist of electromagnetic waves and behave somewhat like x-rays, although their wavelength in general is much shorter. They are less damaging, quantity for quantity, than alpha and beta rays, but have a much greater penetrating power, and so are a major problem.

These rays consist of individual bundles of energy, or quanta, with the amount of energy in each quantum being proportional to the frequency or inversely proportional to the wavelength. As the wavelength decreases, the energy — therefore the penetrating power — increases.

Effective shielding against gamma rays requires the use of a very dense material. The more dense it is, the more effective the shielding properties. For this reason, lead is widely used. A lead shield is about 11 times as effective as the same thickness of water, and half as good as a similar thickness of gold. It has been found that about six inches of lead will effectively shield the most penetrating gamma rays.

Three other particles may be encountered in certain nuclear reactions, such as cosmic ray showers and the output of high-energy accelerators. These are neutrons, positrons, and mesons. Of the three, neutrons are by far the most common, as they are very plentiful in atomic reactors and in the explosion of atom or hydrogen bombs.

Partly because of its lack of charge, a beam of neutrons has very great penetrating power. The penetration depends not so much on the density of the shielding material as on its composition. Any material containing hydrogen, such as water, or the human body, absorbs neutrons to a much greater degree than lead. Thus, a beam of one-million-volt neutrons is slowed down only slightly by a foot of lead, while the same thickness of water will form an effective shield. Three feet of water will absorb even a very high energy beam. Neutrons do not ionize directly but produce ionization by transferring their energy to the nuclei which they strike. These moving, charged nuclei produce the ionization which is then detected by suitable instruments.

High-energy neutron generators such as the cosmotron and betatron are usually shielded with water tanks. Gamma rays ordinarily accompany the production of neutrons and these rays readily penetrate water. For this reason, concrete shielding is included for additional protection.

When a positron and an electron combine, two oppositely directed quanta, or gamma rays, are formed, each with an energy of about half a million electron volts. In this reaction, Einstein's equation setting forth the equivalence of mass and energy is verified, as the energy produced is exactly equivalent to the mass of the electron plus the mass of the positron.

Mesons have tremendous penetrating power. The mesons in cosmic rays can pass through material equivalent to about 30 feet of water or three feet of lead. Large accelerators are usually designed so that any mesons which are generated are fired at a great thickness of earth or concrete. Since mesons do not exist in ordinary nuclear reactions, the shielding problem is not expected to be severe in industrial applications for many years.

Radioactivity

Probably the best-known naturally radioactive materials are radium and uranium. Radium has been used in the laboratory and in hospitals for many years because of its therapeutic effect in cancer and other illnesses. Uranium has received a great deal of publicity as a result of its use in the atomic bomb, as has another radioactive element, plutonium. There are quite extensive deposits of uranium throughout the world; radium is much scarcer; and plutonium, for the most part, is obtained from certain nuclear reactions only and does not exist in appreciable quantities in nature.

In dealing with radioactive materials, we come across a very interesting phenomenon. Regardless of what we do physically or chemically to these materials, we cannot change the rates at which they disintegrate. Every radioactive material, whether naturally or artificially radioactive, has a characteristic rate of decay which cannot be altered by high temperature, pressure, chemical combination, or any other known process. This brings us to a concept known as half-life.

The rate of radioactive decay varies exponentially. If we start with a given quantity of material, half of the material will be gone in a certain length of time, half of what is left will disappear during the next equivalent period of time, etc. We assign a half-life to a radioactive material and define it as the time required for the disintegration rate for a given quantity to decrease to one-half its original value. This, then, gives us a yardstick for comparing the lives of various radioactive elements.

Half-lives vary through a very wide range — from a fraction of a second to millions of years. Radium has a half-life of about

1,590 years, and ordinary uranium about 4.6 billion years. Radon, a radioactive gas resulting from the disintegration of radium, has a half-life of 3.825 days.

Artificial radioactivity may be induced in many different materials by bombarding with alpha rays, neutrons, protons, or other particles. In general, such a bombardment results in a transmutation of the nucleus, and the formation of a different element or an isotope which is radioactive. We will be concerned primarily with bombardment by neutrons, since the large majority of the radioactive isotopes (usually called radioisotopes) in use today are made by such bombardment.

A typical example of artificial radioactivity is the production of radioactive sodium ($_{11}Na^{24}$) by bombarding pure aluminum ($_{13}Al^{27}$) with neutrons. An alpha particle is given off in the process, and the radioactive isotope of sodium which is produced has a half-life of 14.8 hours. The original reaction may be written as follows:

$$_{13}Al^{27} + {_0n^1} \rightarrow (_{13}Al^{28}) \rightarrow {_{11}Na^{24}} + {_2He^4}$$

The compound nucleus indicated by the symbol in parenthesis is introduced for convenience.

Not all isotopes formed by neutron bombardment are radioactive. For example, the bombardment of boron ($_5B^{10}$) by neutrons gives stable lithium ($_3Li^7$), and an alpha particle. This reaction is commonly used as a test for neutrons.

Nuclear fission, mentioned briefly in Chapter 1, provides the basis for the operation of nuclear reactors and the explosion of atomic bombs. When a neutron strikes the nucleus of a fissionable material the nucleus disintegrates, giving off two or three neutrons along with a tremendous amount of energy. If each of these neutrons in turn strikes other nuclei to produce still more neutrons, we have the possibility of a chain reaction. In the atom and hydrogen bombs, this chain reaction is encouraged and allowed to proceed uncontrolled; in nuclear reactors, the fission process is kept under control at all times by controlling the number of available neutrons. The uranium isotope $_{92}U^{235}$ (which can be abbreviated U^{235}) and plutonium are the most widely used fissionable materials. When a fissionable atom breaks down due to the fission process many different elements may be formed, including krypton and barium.

Standards

This brief discussion of both natural and artificial radioactivity will serve as a background for considering various methods of measuring atomic radiation, one of which is the relative effect on the human body. For a proper appraisal of the many factors involved, we will need to make use of some of the standards which have been established in the field of radioactivity.

The curie is a basic unit of measurement which is encountered frequently. The technical definition of a curie is the amount of activity of radon gas in equilibrium with one gram of radium. It is equivalent to the total rate of emission of alpha particles from one gram of radium, if all by-products are separated as rapidly as they are formed. Originally the curie was intended to be applied to radium only, but its use for making measurements with all radioactive materials is widespread. The commonly accepted definition is that one curie is the amount of radioactivity which will produce 37.1 billion (3.71×10^{10}) disintegrations per second. For convenience, lower rates of disintegration can be measured in millicuries (mc) or microcuries (μc). One mc equals 1/1000 curie, which is 3.71×10^7 disintegrations per second. One μc equals 1/1,000,000 curie, which is 3.71×10^4 disintegrations per second.

Another unit of measurement is called the rutherford (rd). This is equivalent to one million disintegrations per second. For convenience in measuring both larger and smaller amounts of radioactivity, there are other related quantities. These are:

Quantity	Symbol	Relation to Rutherford	Disintegrations per Second
Megarutherford	Mrd	One million rd	10^{12} (1 trillion)
Kilorutherford	Krd	One thousand rd	10^9 (1 billion)
Rutherford	rd	One rd	10^6 (1 million)
Millirutherford	mrd	One thousandth rd	10^3 (1 thousand)
Microrutherford	μrd	One millionth rd	1

The relationship between the two units of measure are:

$$\text{One curie} = 3.71 \times 10^4 \text{ rutherfords} = 37.1 \text{ Krd}$$

$$\text{One rutherford} = 2.7 \times 10^{-5} \text{ curie} = 27\ \mu c$$

Radioactive isotopes are ordinarily purchased by curies or millicuries. Thus, one millicurie of radioactive iodine is that amount which produces 37.1 million disintegrations per second. It is well to note that the products of disintegration do not enter into the definition, only the number of disintegrations per second is involved.

The National Bureau of Standards is custodian of our standards of radioactivity. A special laboratory has been constructed for radioactive cobalt standardization, because of the comparative low cost and availability of this isotope. The Bureau also distributes various other radioisotope standards at nominal prices. Fig. 2 - 1 shows a group of such standards.

Another important measurement is the total quantity or dose received when an object such as the human body is exposed to radiation. A unit called the roentgen (r) has been established for this measurement. It indicates the ionizing ability of the rays, which is a direct measure of their effect on the human body. The technical definition states that one roentgen is that quantity of radiation which

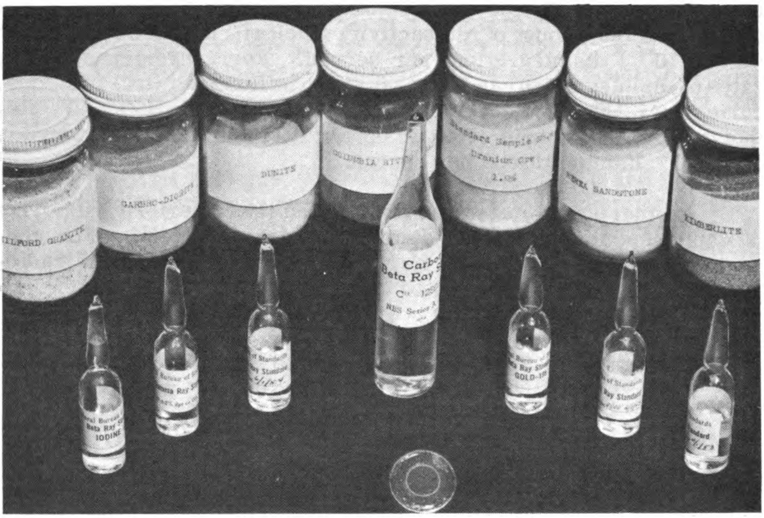


Fig. 2-1. A Group of Radioactive Standards Available from the National Bureau of Standards.

produces one electrostatic unit of electricty of either sign per cubic centimeter of air at standard pressure and temperature. In average tissue, one roentgen will produce an ionization equivalent to an energy concentration of 93 ergs per gram. For our purposes, it should be remembered that the higher the intensity in roentgens, the greater will be the number of ion pairs formed in human tissue, and the greater will be the damage to the tissue.

As the roentgen is rather a large unit for some measurements, the milliroentgen (mr, one one-thousandth of a roentgen) is frequently used. The abbreviations rep and rem are also encountered occasionally. Rep stands for "roentgen equivalent physical", and is based on the energy production of radiation; rem is the abbreviation for "roentgen equivalent man", and is based on the equivalence of biological effects.

Some types of radiation are more damaging to the human body than others. In order to reduce all measurements to a common denominator, the relative biological effectiveness (RBE) of various rays must be considered. Beta and gamma rays are used as a basis and the RBE of each is one. Neutrons are much more destructive to

human tissue, partly because of their penetrating power, and are considered to have an RBE of about 10. Alpha rays given off by radioactive materials within the body have an RBE of 20.

Most instruments in common use for measuring radiation indicate the intensity or rate of exposure, rather than the total dose. Calibration is thus made in roentgens per hour, or milliroentgens per hour. To obtain the total dose, the intensity is multiplied by the time of exposure. For example, if a person is exposed to a radiation of 2 milliroentgens per hour (mr/hr) for an 8-hour period, the total dose would be 16 milliroentgens.

Because of the penetrating power and range of gamma rays, the roentgen is not suitable for use if more than 2 or 3 mev of energy is involved. Between 2 and 100 mev, the intensity is usually indicated in watts per square centimeter, and radiation exposure in watt-seconds per square centimeter. The dose rate is watts per gram. However, most radiation normally given off by radioactive materials has an energy of less than 2 or 3 mev, so the roentgen is still widely used. The error is small up to 30 or 40 mev.

Radiation Effects on Humans

It has been known for many years that excessive exposure to x-rays or to radium produces many harmful effects in the human body, such as reduced blood count and inflammation of the irradiated area. It is also known that the results of such radiation can be cumulative, i.e., the effects of many small doses over a long period can add up to the same effect as a large dose in a short period. A tremendous amount of research and effort has been expended in determining just how much radiation the human body can stand with neither short-range or long-range harmful effects. Data has been accumulated from the time x-rays and radioactivity were first discovered, and innumerable experiments have been conducted on animals of various kinds. On the basis of all this evidence, standards have been set up and maximum dosages prescribed which indicate safe limits.

The standard limit has been set at 0.3 roentgen per week, based on an eight-hour day, five days a week. This would permit a lifetime exposure of 432 roentgens, assuming 30 years service and a 4-week annual vacation. It is interesting to note that normal exposure to cosmic rays and natural radioactivity results in a dose of about 0.3 milliroentgens every 24 hours. A conventional chest x-ray represents a dose of 1 to 3 r per film, a chest fluorogram 5 to 10 r, and a full mouth dental x-ray about 180 mr.

Because of the cumulative effects, a dose in excess of .3 r in any week should be followed by a period of reduced exposure so that the over-all average does not exceed the specified weekly limit, and the lifetime exposure is not greater than about 300 - 400 r. It has been fairly well established that if these limits are not exceeded no harmful results will be experienced.

Table I

A Basic Working Guide Which Indicates Results that Can Be Expected After Exposure to Various Doses.

Dose (roentgens)	Time of Dose Accumulation	Immediate Effects	Late Effects
75	1 day to 3 months	none	probably none
100	1 day	sickness in 1 to 2%	probably none
100	3 days to 3 months	none	probably none
150	1 day	sickness in 25%	very slight
150	3 days or more	sickness in less than 25%	very slight
300	1 day	sickness in 100% 20% fatalities	possible cataracts & increased cancer incidence
300	3 days	much less than above	possible cataracts & increased cancer incidence
300	1 week	sickness in 50% no fatalities	possible cataracts & increased cancer incidence
300	1 to 3 months	probably no sickness	possible cataracts & increased cancer incidence
650	1 day	100% fatalities	----------------
650	3 days to one week	sickness in 100% fatalities high	pronounced, serious
650	1 to 3 months	sickness not high fatalities about 10%	pronounced, serious

Effects of radiation can be both immediate and delayed, or late. The late effects may have genetic manifestations, thus possibly influencing later generations. A basic working guide has been set up by the Civil Defense Administration and others which indicates results that can be expected after exposure to various doses. This guide is presented briefly in Table I. It should be taken for what it is — a guide only — and not a positive indication of the exact effects. Tolerances of different individuals vary through a wide range, so no positive statements can be made predicting the exact effects in individual cases.

Internal radiation resulting from contaminated food, water, dust, etc., can be harmful if excessive amounts of such contaminated

material enter the body. Permissible limits for this type of exposure are extremely difficult to set up because of the many variable factors involved. Such factors include the half-life of the radioisotopes present in the material entering the body, the portions of the body in which these radioisotopes concentrate, the length of time they remain in the body, types of radiation given off, and many others. It is perhaps safe to say that internal radiation should not exceed the value of 0. 3 r per week indicated previously for external exposure.

An excellent discussion of this subject, together with a table giving maximum permissible amounts of various isotopes which can be taken internally under various conditions was published recently. * This article should be reviewed if more detailed information is desired. Bulletins published by the Federal Civil Defense Administration give information on the maximum levels which can be tolerated on an emergency basis. For example, water or food containing a maximum of 0. 03 microcuries per cubic centimeter (. 03μc/cc) may be used for a period of one month when beta-gamma activity is involved. For alpha activity, the amount must be reduced to 0. 0017 μc/cc. This latter figure represents 60 disintegrations per second per cubic centimeter (dps/cc).

It is reassuring to learn that there have been very few injuries due to excessive radiation in all the widespread activities of the Atomic Energy Commission. The average annual exposure of all Hanford — Oak Ridge workers (0. 2 r a year) is less than the normal exposure to cosmic rays in Denver, Colorado (0. 5 r a year).

Radiation affects many things besides the human body. For example, radiation will speed up the mutations in both plant and animal life, because of its effect on the genes controlling various hereditary factors. It can affect the polymerization of plastics, sometimes favorably, sometimes unfavorably; and can alter the properties of fabricated plastic materials. Some metals will have their characteristics altered by continuous exposure to high-intensity radiation. Sterilization of certain drugs, such as penicillin, can be facilitated by proper use of radiation.

Intensive research programs aimed at answering questions raised by radiation problems are in full swing throughout the country. Some answers are being discovered at the materials testing reactor, operated by the Atomic Energy Commission. However, complete answers will not be forthcoming until a great deal more research and experimentation has been carried out.

---

* "Developments in Internal Dose Determinations" by K. Z. Morgan and M. R. Ford, Nucleonics June, 1954.

CHAPTER 3

Radiation Detection Devices

Atomic radiation has many different characteristics which may be exploited in developing detection and measuring instruments. Such devices as cloud chambers, ionization chambers, Geiger tubes, and electroscopes depend on the ionizing properties of the rays for an indication of intensity. Some crystalline substances, for example, sodium iodide, will give off flashes of light, or scintillate, when struck by atomic radiation. Other crystals, including diamonds, will change resistance upon being irradiated. Certain chemical indicators will change color to a degree dependent upon radiation intensity. Photographic film is sensitive to radiation.

These and other phenomena have been applied in experimental and commercial detectors. The discussions in this chapter will include the basic devices and techniques most commonly used.

Cloud Chamber

Probably the first and most widely used instrument for studying various kinds of rays and particles is the Wilson cloud chamber, named after the British physicist, C. T. R. Wilson. It operates on the principle that when air saturated with water or other vapor is expanded suddenly, the air becomes supersaturated and tiny droplets condense upon dust or any other particles which are present. These droplets persist long enough to be photographed. Ions are ideal as nuclei for condensing droplets. The air in the chamber is made dust-free and the ionizing rays under study are introduced. When expansion takes place, a droplet is formed around each ion along the path of the ionizing rays, thus indicating the exact paths of the rays.

An alpha particle ionizes very heavily, and so produces a dense path of droplets. Beta particles ionize much less heavily, resulting in a much sparser number of droplets. Gamma rays ionize only very slightly, and so form only a few droplets as they pass through the chamber.

By applying an external magnetic or electric field to the chamber, the rays may be deflected, and the velocity of the particles

making up the rays can be measured when field strengths are known. This technique has been applied in determining the energy of particles resulting from collisions, and for detecting new particles which may result from nuclear reactions.

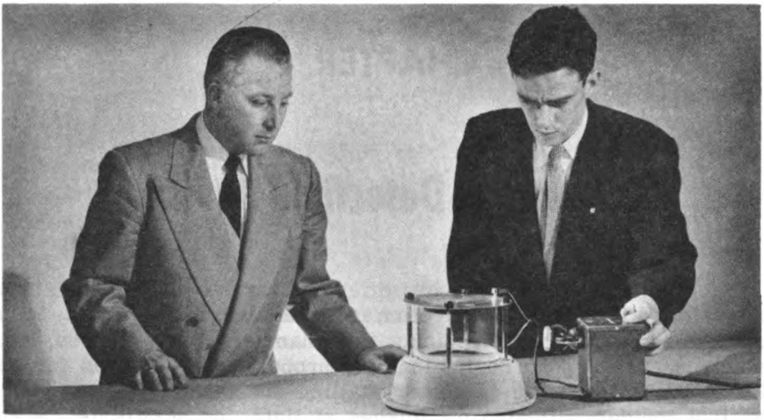


Fig. 3-1. The "Cloudmaster", A Continuously Sensitive Cloud Chamber Which Provides a Spectacular Display of "Tracks" Caused By Alpha, Beta, Gamma and Meson Radiation. (Courtesy of Nuclear - Chicago.)

A commercial cloud chamber, called the "Cloudmaster," is shown in Fig. 3-1. This unit displays ionizing radiation tracks by maintaining a continuously supersaturated region of isopropyl alcohol vapor near the bottom of the chamber. Droplets form around any ions produced in this region. A strong light assists in observing the tracks. Electrons are swept out of the chamber by a 1200-volt potential, so that droplets are formed on the positive ions only. A radiation source is provided with the unit, but even when this source is removed, occasional tracks can be distinguished. They are caused by high energy cosmic rays.

Ionization Chambers

As the name indicates, ionization chambers depend on the ionizing properties of radiation for their activation. In general, an ionization chamber consists of a cylindrical enclosure of metal or of glass coated inside with some conducting material, and with a coaxial rod or wire located centrally within the cylinder and insulated from it. The total enclosure is sealed, and may contain air, argon, or other gases at various pressures up to and greater than atmospheric, depending on the specific use for which the chamber is constructed.

The central conductor is operated at a positive potential with respect to the outer enclosure. When ions are formed as a result

of exposure to ionizing radiation, the positive ions are attracted to the negative outer enclosure, and the negative ions (usually electrons) are attracted to the center conductor. Thus, a current can be made to flow in an external circuit. The magnitude of this current depends on the amount of ionization.

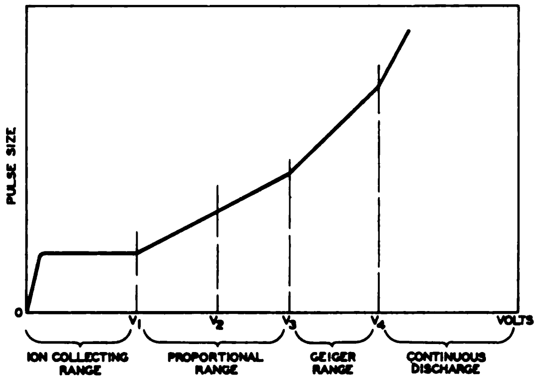


Fig. 3-2. Diagram Showing How Various Voltages, Applied to a Tube Circuit Such as Shown in Fig. 3-3, Will Produce Different Pulse Sizes for a Constant Amount of Incident Radiation. (Courtesy of National Bureau of Standards.)

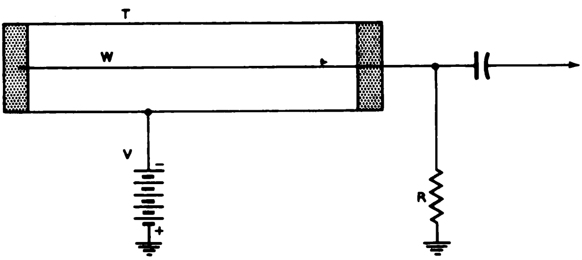


Fig. 3-3. Schematic Diagram of a Geiger Tube, Which May Be Operated Either in the Proportional Region or the Geiger Region. (Courtesy of National Bureau of Standards.)

Fig. 3-2 shows the relative amplitudes of current pulses which can be expected at various voltages for an ionization chamber connected in a circuit such as that shown in Fig. 3-3. For this analysis, assume that there is a constant value of incident radiation which is affecting the tube.

There are four general voltage ranges where radiation can be detected. The tube operates differently in each of the four ranges.

No exact voltages have been assigned to this diagram, but there is a set of voltages which will apply for each style and size of tube which may be used.

In the first section, from 0 to V_1, pulses are formed from the ions which are produced directly from incident radiation. When the voltage across the tube is 0, there is no force which will draw the ions into the external circuit, so no current pulses are formed. As the voltage is increased to very low values, some of the ions will pass through the external circuit; pulse amplitude here depends on the portion of available ions which are attracted. The remainder of the ions will recombine without passing through the external circuit. As voltage across the tube continues to increase, larger portions of the available ions will be attracted to the external circuit. Soon the voltage is high enough to attract all the ions which are produced by the incident radiation. This is the beginning of the horizontal line in the diagram, known as the saturated region. As the voltage is increased through the saturated region, the ions will travel through the tube at greater speeds, but the total volume, and therefore the pulse size, will remain the same.

When the voltage is increased above the value V_1, additional ions become available to form the current pulses. The increased speed of the original ions, travelling through the tube, will cause additional ionization to occur by collision. Because of the geometry of the tube chamber, the strongest field is close to the center conductor, or wire. So most of the additional ionization takes place in the immediate vicinity of the wire. Such ionization, caused by a series of successive electron collisions, is called an electron avalanche. At any particular voltage in the proportional range, the avalanches produced by individual electrons are similar to each other. The net effect, then, is to amplify the original pulse size. This is called gas amplification. An ionization chamber operated in this region is called a proportional counter because the resulting pulse size at any particular voltage is directly proportional to the number of ions formed due to radiation. Amplification factors as high as 1000 to 10,000 are possible. The curve in Fig. 3-2 shows that the resulting pulse size, and therefore the amplification factor, increases gradually through the range of applied voltages from V_1 to V_3.

Beginning at the point identified as V_3, each ionizing event, no matter how small, will initiate an electron avalanche which spreads quickly through the entire tube. This point is called the Geiger threshold, and the section of the curve from V_3 to V_4 is known as the Geiger range. Characteristic operation in this range calls for one large pulse for each ionizing event to which the tube is subjected. The pulse size does not depend on the amount of radiation from the outside source, but it does increase as greater voltages are applied. When voltages applied to the chamber are great enough to cause this condition, the chamber is operating in the Geiger region, and is called a Geiger tube.

If a voltage greater than V_4 is applied to the tube, a single ionizing event, no matter how small, will produce an ionization in the

tube which will not stop. This is called the Continuous Discharge region. There is no value in using this region of operation because there is no relation between the current through its external circuit and either the quantity or the amplitude of ionizing events.

When the voltage is less than V_3, the pulse amplitude is proportional to the amount of incident radiation. In the Ion Collecting range, this is very small, and it is difficult to measure it with conventional equipment. Insulation resistance must be extremely high, and the measurement method must not take any power from the chamber circuit. Sometimes an electroscope can be used to measure the pulses, or the current may be amplified to a readable value with an electrometer tube.

When we deal with radiation, we are frequently concerned with a single particle, or quantum, and the resulting ionization. Such ionization produces a single pulse of current in the external circuit, since all of the ions are formed almost simultaneously. Therefore, it is necessary to consider pulse size or pulse magnitude resulting from a single ionizing event. Pulse sizes below the saturated region are small and variable, but pulse size in the horizontal portion of the curve is constant for a given quantity of ionization. Incoming rays lose approximately 32 ev of energy for every ion pair formed. Assuming that all the energy is used to form ions within the chamber, rays with equal energy will form equal pulses. Conversely, if the rays have unequal energies, various pulse sizes will be produced. The individual pulse size then indicates the number of ions formed by each ionizing event.

In the proportional range, pulse size is still directly related to the number of ions in the ionizing event. But the amplitude of each pulse is greater because of gas amplification. This makes it easier to measure the relative pulse sizes with conventional equipment. Usually two stages of pulse amplification are sufficient to operate headphones or a meter.

When the tube is operating in the Geiger region, there is no relationship between the amplitude of incident radiation and the size of an output pulse. There is, however, one output pulse for each ionizing event. The pulse amplitude is large enough to operate headphones or a meter without any amplification.

The curve of Fig. 3-4 shows the performance of a typical Geiger tube over a wide range of voltages. As can be seen, there is quite an extensive region of operation where relatively large changes in voltage produce only slight changes in pulse size. This is known as the Geiger plateau, and the slope and length of this plateau give an indication of the condition of the tube. Ordinarily, the plateau should be at least 100 volts long, and the slope should not be greater than about 0.01% per volt.

Geiger Tubes

Although Geiger tubes are ionization chambers, strictly speaking, they will be discussed under a separate heading as they are used so very widely and have so many characteristics which are typical and do not apply to other types of counters. A schematic diagram of a Geiger counter is given in Fig. 3-3.

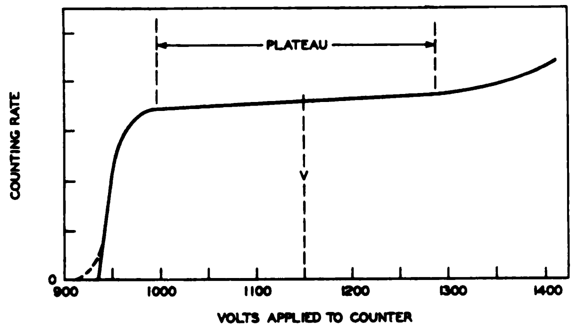


Fig. 3-4. Curve Showing the Operating Plateau of a Typical Geiger Tube. (Courtesy of National Bureau of Standards.)

When a tube is operated in the Geiger region, a discharge, once started, will continue unless something is done to quench or extinguish it. One technique is to make the load resistor R (Fig. 3-3) so large that the voltage drop across it reduces the counter voltage below the point where continued ionization can take place. Other types of external circuitry can also be applied to produce quenching, but self-quenching counters are used almost exclusively and will be discussed in some detail in the following paragraphs.

If an organic gas such as alcohol vapor is introduced into a Geiger tube, it has the ability to stop the ionizing process once the original discharge has taken place. Alcohol ions, when they reach the center conductor, are neutralized and then dissociated rather than forming new electrons for continuing the discharge. Thus, organic quenching takes place, and the external resistor R in Fig. 3-3 can be arbitrarily low in value, a very desirable condition.

One disadvantage of this type of quenching is that some of the organic material is used up every time a discharge takes place. This places an upper limit on the life of the tube. Counts of the order of 10^8 to 10^{10} (one hundred million to ten billion) are typical for organically quenched tubes.

Recently a new technique, called halogen quenching, has come into widespread use. This technique has one tremendous advantage over organic quenching — the life of the tube is not limited by the quenching material. The quenching mechanism involves only a change

in the halogen gas from the molecular to the atomic state and back again — none of the halogen is consumed in the process. One company manufactures tubes which have operated for as many as 10^{14} counts with no substantial change in characteristics. Originally halogen quenching was subject to disadvantages, but these have been overcome in current designs. For example, the sensitive volume of the counter is reduced slightly — to about 80-95%, depending on the type

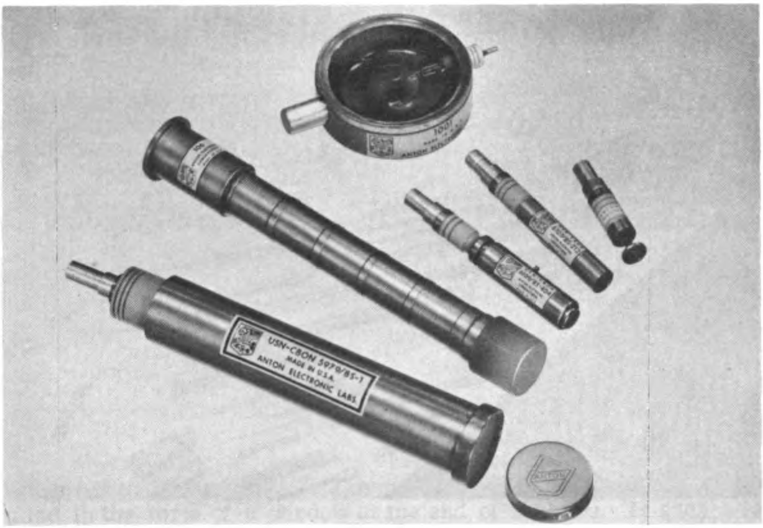


Fig. 3-5. An Assortment of Halogen Quenched Geiger Tubes. (Courtesy of Anton Electronic Labs.)

of tube. This is now considered in original calibration. Also, the slope of the counting plateau is slightly greater than that attainable during the early life of organic quenched tubes. This latter disadvantage is readily overcome by the use of regulated power supplies.

The quantity of halogen in a halogen counter is limited to a few micrograms. Halogen gases (chlorine, bromine, etc.) are very active chemically, so tubes must be engineered and built to prevent even these infinitesimally small quantities from reacting with the envelope and other elements. For example, one manufacturer uses stainless steel construction with ceramic insulators.

When properly made, halogen-quenched Geiger tubes will give satisfactory performance over a temperature range of $-50^{\circ}C$ to $+75^{\circ}C$, because the physical state of the gases utilized is not affected through this range. The tubes can neither be damaged by sustained overcurrent nor limited in life by operation. A group of typical halogen-quenched Geiger counter tubes is shown in Fig. 3-5.

Common materials used for Geiger tubes envelopes are stainless steel, aluminum, and glass. When glass is used, the inside wall is coated with a conducting material such as aquadag. The inner wall of the envelope is, electrically, the negative terminal for the tube. A group of miscellaneous types of counter tubes is shown in Fig. 3-6.

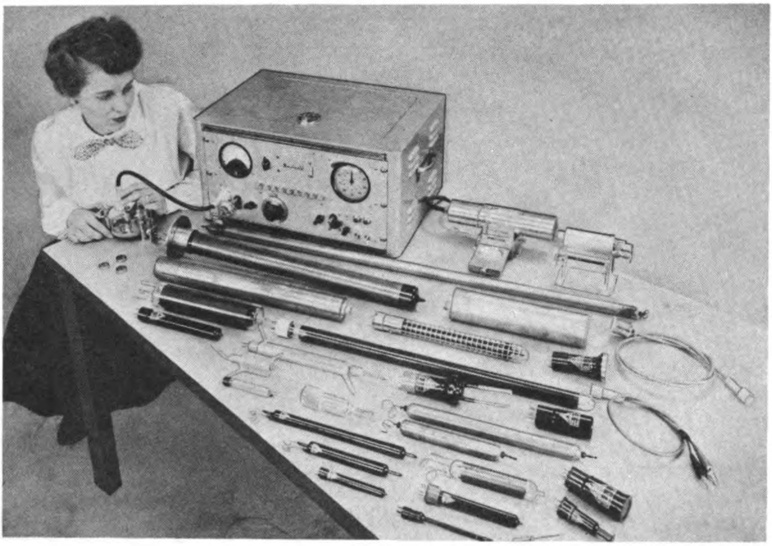


Fig. 3-6. A Miscellaneous Group of Counter Tubes.
(Courtesy of Radiation Counter Laboratories, Inc.)

Wall thickness for the envelope is determined by the type, or types, of radiation to be measured. The thickness is specified in terms of weight per unit area of envelope material, such as milligrams per square centimeter (mg/cm^2). This method of specifying wall thickness relates the penetrating power of atomic radiation and the ability of the wall to withstand penetration.

All commonly encountered alpha and beta radiations are held back by a wall thickness of about 300 mg/cm^2, but gamma rays will pass through it. So this is a common wall thickness for Geiger tubes designed to measure gamma radiations. There is an adequate mechanical strength when any of the commonly used materials are made into envelopes with this wall thickness.

Stainless steel tubes and some small glass tubes are strong enough mechanically when they have wall thicknesses as thin as 30 mg/cm^2. Glass wall tubes like this admit all gamma radiations and most beta radiations, but exclude the weaker beta rays and all alpha radiations. Stainless steel tubes with walls this thin are common

and have similar ray separating characteristics. The beta particles from strontium^{90} have an energy of 0.65 mev; when they are directed at a wall thickness of 30 mg/cm^2, 31% of them will pass through the wall. At an energy of 1.712 mev, 72.4% of the beta particles will be admitted through the wall.

Table II

Calculated Energies Required for Alpha Particles to Pass Through Various Mica Window Thicknesses, and Corresponding Alpha Ray Range in Air. (Courtesy of Anton Electronic Laboratories Inc.)

Window thickness mg/cm^2	Alpha initial kinetic energy (mev)	Mean alpha range in air (cm)
1.4	greater than 1.9	greater than 1.0
2.0	2.6	1.5
3.0	3.6	2.2
4.0	4.5	2.9

Mechanical considerations prevent the utilization of walls much thinner than 30 mg/cm^2. If a thinner wall is desired, it may be applied in the form of a window at the end of the tube. In such a location, the thickness can be reduced considerably while still maintaining adequate mechanical strength. Windows are commonly made of such materials as mica, glass, stainless steel, and pliofilm. Window diameter varies, but may be as great as 1 1/2 inches.

For measuring alpha radiation, the window thickness is generally less than 5 mg/cm^2. Since the range of alpha particles is very limited in air, the source of radiation must be placed close to the window in order to obtain a true indication. Table II indicates the alpha particle energy required to penetrate various window thicknesses. The ranges in air for these alpha particle energies are included for comparison. As an example, if the window thickness is 2 mg/cm^2, at least 2.6 mev of alpha particle energy is required for the alpha particle to pass through the window and into the ionization chamber. An alpha particle with 2.6 mev of energy could pass through 1.5 centimeters of air.

Many times it is desirable to use a single tube for different applications. For example, it may be desirable to measure beta radiation in the presence of gamma radiation, and vice versa. Such measurements can be made with a tube designed for beta-gamma counting (thin wall — about 30 mg/cm^2) by providing a sliding cover for cutting out the beta rays without eliminating the gamma rays. A

measurement with the cover removed then indicates both beta and gamma intensity, and with the cover in place, gamma intensity alone. By subtracting gamma from the total, beta intensity is obtained. The same principle can be applied to end-window tubes. Shields of different thicknesses placed over the window provide selective absorption.

With the large scale use of high-energy particle accelerators and reactors, the measurement of neutrons has become very important. Since neutrons produce very little ionization in a gas, some other method of detection must be used. A common technique is to fill a conventional tube with boron trifluoride gas (BF_3) under pressure, particularly when thermal (slow) neutrons are to be measured. The boron contains a high percentage of the isotope B^{10} and has a high neutron capture cross section, i.e., it captures a high percentage of neutrons traveling through the chamber. When a neutron strikes a B^{10} nucleus, a nuclear reaction takes place as brought out in Chapter 1. The resulting products are a lithium atom and an alpha particle having an energy of nearly 3 mev. This alpha particle ionizes the gas and produces a pulse in the output circuit. Another technique is to line the walls of the tube with metallic boron. The reaction is the same as when BF_3 gas is used.

Gamma rays are very inefficient ionizers of gas in a counter tube. Practically all of the ionization is due to secondary electrons emitted from the walls of the tube, and direct ionization of the gas is negligible. To increase the number of secondary electrons produced by the gamma rays, the walls of the tube are made as thick as possible without introducing too much loss. Also, the tubes are sometimes lined with bismuth or other material to increase efficiency further.

Operating potentials for Geiger tubes vary from 300 volts to 1500 volts or more, depending on individual design. Current requirements vary with the intensity of the radiation—the higher the counting rate, the higher the current drain. In general, the current through the Geiger tube and load resistor will be a few microamperes at most. The load resistance in series with the tube is around one to ten megohms, and individual pulses will produce a peak output of about one volt, sufficient to give an audible signal in headphones without any amplification.

Electroscopes and Electrometers

An electroscope takes advantage of the fact that like charges repel each other. In the simplest unit of this type, called the gold leaf electroscope, the leaf and its support are insulated from the container and all other materials and charged to a potential of several hundred volts. The leaf is repelled from the support and remains in a repelled position until the charge disappears. If the insulation is very good and there are no ions present, the charge will leak off very slowly. However, if ionizing radiation is present, the charge will

leak off more rapidly. The rate at which the gold leaf falls back towards the support then gives an indication of the intensity of radiation.

The Lauritsen electroscope, diagrammed in Fig. 3-7, represents a big improvement over the gold leaf electroscope. The sensitive element consists of a fine metallized quartz fiber, mounted on an insulated parallel metal support which may be charged from a battery

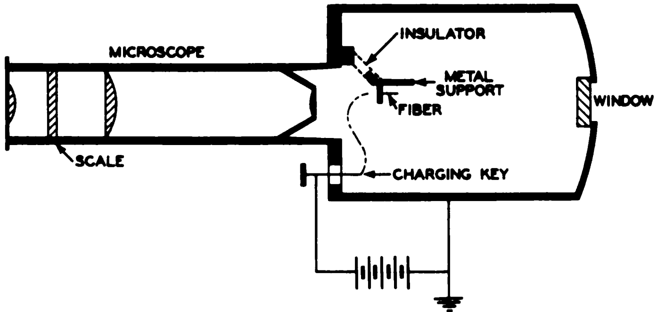


Fig. 3-7. Diagram of the Lauritsen Electroscope.
(Courtesy of National Bureau of Standards.)

or other source of potential. A small piece of quartz fiber mounted across the end of the metallized fiber serves as an index that is viewed through a microscope with eyepiece scale. On being charged, the metallized fiber is deflected from the support and returns toward the position of zero charge when the gas in the chamber is ionized. About 200 volts is required to produce full-scale deflection. Sensitivity is about two divisions per minute for one milligram of radium at one meter.

Electroscopes require steady auxiliary potentials to produce electrical fields when measurements are started. As radiation causes ionization, which reduces the field intensity, the indicating fiber changes its position. The fiber is sometimes called a "needle".

Electrometers indicate radiation presence with a moving needle also. But this needle is the pointer of a voltmeter. When it is connected to an ionization chamber, the electrometer indicates the chamber potential. The rate at which the needle moves is determined by the amount of ionization produced per unit of time in the chamber, and this is determined by the radiation intensity.

Electrometer tubes are widely used for amplifying extremely small DC currents. Tubes have been especially developed which operate with very low grid currents and have high insulation of the control grid. Such a tube, the type FP-54, is used in the DuBridge-Brown circuit shown in Fig. 3-8. The tube operates with a very low value of filament-to-plate voltage (4 to 5 volts), and yet it will amplify currents as small as 10^{-14} ampere (0.01 micromicroampere) to readable values. This limit can be extended so that it is possible to measure very small amounts of ionization with the equipment under special conditions.

Fig. 3-8 shows that a 12 volt DC source is enough to furnish both filament and plate voltages for the DuBridge-Brown circuit. This makes it possible to make an electrometer a compact, completely portable instrument. The "G" in the diagram is a sensitive galvanometer which will register plate current for the tube.

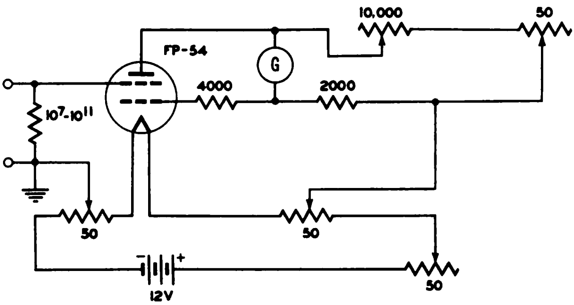


Fig. 3-8. Du Bridge-Brown Electrometer Circuit for Use with the FP-54 Electrometer Tube. (Courtesy of National Bureau of Standards.)

The electrometer requires a separate ionization chamber for measurement of ionizing radiation. Current pulses from the ionization chamber are connected to the electrometer circuit across the high value of grid resistance. The terminals for chamber connections are shown at the left hand side of Fig. 3-8.

Scintillation Crystals

Certain materials will give off small flashes of visible light when struck by alpha or beta particles, gamma ray quanta, or neutrons. These flashes, which are called scintillations, may be detected and counted by a photoelectric cell of the photomultiplier type, thus giving an indication of the intensity of radiation in the vicinity. Table III lists some of the more commonly used scintillation crystals and gives their basic characteristics.

Sodium iodide (NaI) is widely used for the detection of gamma rays because of its high light output and efficient gamma ray absorption. A small amount of thallium (Tl) is usually added to NaI crystals as an activator to shift the flourescence into the spectral region most easily detected by photomultiplier tubes. The symbol for sodium iodide activated in this way is usually written NaI (Tl). Since this material is highly deliquescent (absorbs moisture from the air), it is normally supplied in a hermetically sealed container.

Counters using scintillating crystals, called scintillation counters, have many advantages over other types. Such counters will be given a detailed treatment in Chapter 5.

Conducting Crystals

Some crystalline materials become slightly conducting when subjected to atomic radiation. Only crystals which are normally nonconducting can be used as radiation indicators because the conduction current is very small. The first experiments for investigating this property were made on crystals of silver chloride at the temperature of liquid air. Since then, it has been found that diamonds exhibit these characteristics at room temperature.

In practice, the crystal is clamped lightly between two electrodes and a polarizing voltage of several hundred volts applied. A pulse is then produced whenever the crystal is struck by an alpha or beta particle or a gamma ray quantum. The pulses developed are all small but have a considerable range of magnitude. Therefore, a relatively high gain amplifier is required to produce a usable output.

Table III

The Most Common Crystals Useful as Scintillation Counters. (Courtesy of National Radiac Inc.)

Scintillator Material	Principal emission spectrum, angstroms	Relative Light Yield to beta rays	Decay Constant x 10^{-8} second	Density	Melting Point ^{o}C
Anthracene	4440	1.0	3.0	1.25	217
Diphenyl acetylene	4100	.8	0.4	1.18	63
Stilbene	4080	.65	0.8	1.16	126
Terphenyl	3900 4050 4300	.6		1.23	214
Sintilon brand plastic phosphor	4600	.6	.8	1.05	110
Sodium iodide activated with Tl	4100	2.0	25	3.67	651
Naphthalene	3450	.25	6.0	1.15	80
Potassium Iodide activated with Tl	4100	.5	100	3.13	582
Calcium Tungstate	4300	1.0	300	6.06	1530

This method of measurement has not seen widespread use outside the laboratory, although it appears to have certain advantages in the measurement of gamma radiation. Because of the high density of the crystal, the gamma sensitivity is much higher than with ionization chambers. The crystal has a tendency to polarize, so that the magnitude of the output pulses decreases with continued use.

Chemical Indicators

Some solids and liquids will change color when exposed to atomic radiation, the amount of color change giving an indication of the quantity of radiation absorbed. Alkali halides such as lithium fluoride, potassium bromide, and sodium chloride have been used as chemical integrating indicators for both high energy photons (gamma rays) and nuclear particles.

Chemical indicators apparently are neither sensitive enough nor sufficiently quantitative to be used for most laboratory measurements. However, they appear to have potentialities in the measurement of extremely high levels of radiation intensity, and in dosage indications. Current investigations may result in the development of materials more satisfactory then any used at present.

Photographic Emulsions

Photographic film is one of the most widely used sensing elements for radiation. One example is its application in x-ray photographs of all kinds. It is used extensively in badges for monitoring the dosage of radiation received by personnel, and this aspect will be discussed in greater detail in Chapter 7.

Special types of films have been developed for various purposes. Sensitive films are employed for monitoring low energy beta and gamma rays and insensitive films for high energy rays. Other films are better suited for indicating neutrons. Thick films can be used for detailed studies of the tracks followed by nuclear radiation. Film has the advantage of providing a fairly permanent record of a nuclear event.

Film must be developed before it can be read, and the emulsions must be very carefully controlled if consistency of readings is desired. A densitometer of some kind is necessary to compare the film density with a standard. However, in spite of these disadvantages, improvements are continually being made and film is being more and more widely applied to radiation measurements.

Miscellaneous

There are several other techniques available for the detection and measurement of atomic radiation, but most of them are either in the very early stages of development, or are suitable for use only in laboratories where skilled personnel and highly specialized equipment are available. Three of these techniques will be described briefly in the following paragraphs.

The total amount of energy given off by a radioactive material may be measured by means of a sensitive calorimeter, as all of the energy is eventually converted to heat. However, since the total energy given off per unit time is small except for large quantities of radioactive materials, only highly specialized equipment can

determine this energy with any degree of accuracy. A microcalorimeter has been developed for this purpose which can measure the generation of heat at the rate of 0.005 calories per hour with an over-all accuracy of 2 or 3%.

Barium titanate appears to be affected slightly by nuclear radiation. If a barium titanate crystal is employed to control the frequency of an oscillator circuit, the frequency will shift slightly when the crystal is irradiated. A frequency meter will indicate the amount of frequency change, which shows radiation intensity.

Under suitable conditions, the intensity of alpha and beta rays may be measured by determining the rate at which an insulated receiver accumulates a charge. No gas can be present when such measurements are being made, or ionization may upset the measurements. Relatively strong sources of radiation are necessary; for example, 100,000 beta particles per second is equivalent to a current of only 1.6×10^{-14} ampere.

Many of the techniques described in this chapter have been perfected and applied to instruments of various kinds. Some of these instruments will be described in detail in the following four chapters.

CHAPTER 4

Commercial Geiger Counters

Commercial instruments of the Geiger counter and ionization chamber classes are made in a wide variety of shapes and sizes. Many different types of circuits are used to perform the various functions required in these instruments. Circuits vary from extremely simple to relatively complex, depending on the demands placed on the instrument.

A basic requirement for all counters of this class is a source of high voltage for operation of the counter tube. Some manufacturers have chosen to use high-voltage batteries; others use any one of several kinds of circuitry to step up the output of low voltage batteries to the desired voltage (usually around 900 volts). Current drain at this high voltage is very small, so the circuitry for stepping up the voltage is relatively simple.

Once the output pulses from the counter tube are obtained, the problem becomes one of indicating the pulse rate in some manner. The simplest instruments depend on clicks in a set of headphones or flashes of a neon light; as the circuitry becomes more complex, a meter and integrating circuit may be employed. The integrating circuit serves to smooth out the incoming pulses, which usually are very irregular. It steadies the meter reading to represent the average rate at which pulses are being received.

In laboratory work where very accurate indications of radioactivity are desired, it is customary to count the individual pulses which are produced by the counter tube. An instrument for accomplishing this is called a "scaler", and can be used with any radiation detecting device which provides an individual pulse for each ionizing event. Scalers are made in many different types and sizes; a typical instrument is shown in Fig. 4-1.

Another device which has seen wide use in laboratories is the "ratemeter" or counting rate meter. As its name implies, the instrument indicates the rate at which pulses are received. Calibration is usually in terms of counts per minute, with a number of different ranges ordinarily provided. Since the meter indicates the average

number of counts per unit time, indication will vary as the pulse rate varies. To prevent excessive movement of the meter needle, a smoothing circuit is included with a time constant which smooths out minor and rapid variations, but which permits the meter to follow slower variations. On one commercial instrument, a switch permits selection of 2.5, 10 or 40 seconds for the time constant.

Fig. 4-1. Nuclear - Chicago; Model 161A Scaler. This Instrument Can Count Up to 120,000 Counts Per Minute with Only 1% "Coincidence Loss". Courtesy of Nuclear Instrument and Chemical Corp.

In the following few pages, several representative commercial instruments are described in some detail, and circuit diagrams are presented for analysis. The group is by no means comprehensive, nor does it include all types of circuits, but it includes a number of the different techniques used for obtaining high voltage, and for indicating radiation intensity.

Micro Specialties Co. Model 1U3

This instrument, made by the Cam-Mac Division of Micro Specialties Co., is presented first because of its extreme simplicity, as can be seen from the circuit diagram of Fig. 4-2. A 1B86 Geiger tube, operating at about 300 volts, is used along with a load resistor of 1 megohm. Sensitive crystal headphones connected across the load resistor provide an audible indication of radiation intensity.

High voltage is obtained with a step-up transformer. The relay allows current pulses to be fed through the primary of the transformer from the 6-volt battery. The pulses build up and collapse a magnetic field around the secondary to induce a voltage in it. The build up is relatively slow, and the collapse is more rapid. This causes the secondary to induce more voltage during the period of primary collapse. The higher voltage is sufficient to ionize the gas in the series string

of seven neon tubes and allow current to flow; the lower voltage is not sufficient to cause ionization. This simple circuit rectifies the high voltage and provides DC for the Geiger tube. The 0.1 mfd capacitor

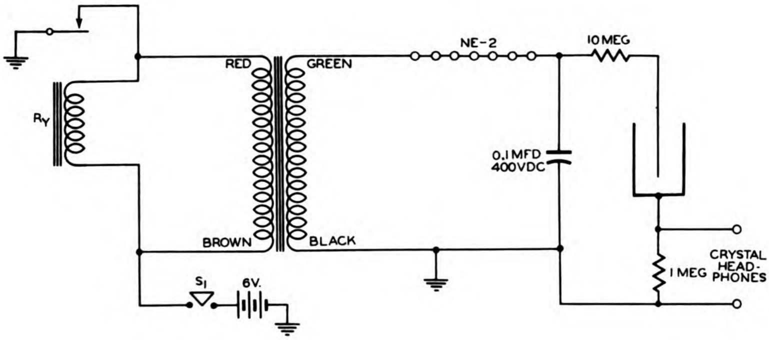


Fig. 4-2. Schematic Diagram of Model 1U3, Made By the Cam-Mac Division of Micro Specialities Company.

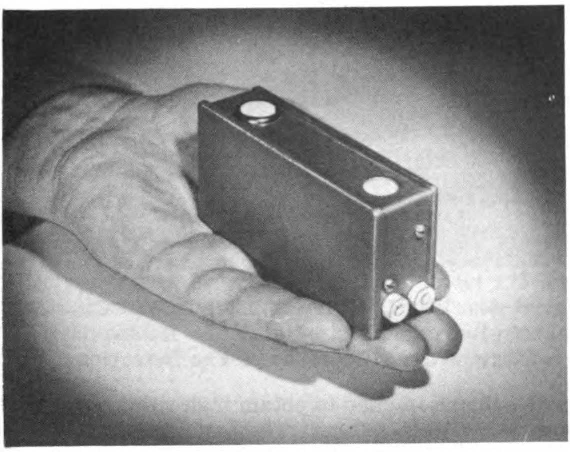


Fig. 4-3. The Model 1U3 Made By the Cam-Mac Division of Micro Specialities Co. Courtesy of Cam-Mac Division Micro Specialities Company.

charges up and holds the DC voltage for application to the Geiger tube through a 10 megohm protective resistor. As shown in Fig. 4-2, the top of the capacitor charges to a positive potential, and the negative potential is connected to the instrument ground.

Because of the extremely low current drain through the counter tube, the 0.1 mfd capacitor will hold its charge for an appreciable

length of time. Consequently, switch S1 need not be depressed continuously but only when necessary, and then only for a short time. This results in low battery drain and long life. Need for more voltage is made evident by the decreasing volume and wider spacing of the clicks in the headphones.

The extremely small size and compactness of this instrument can be seen from the photograph of Fig. 4-3. Single or double crystal headphones may be used, but magnetic units are not recommended.

The Detectron "Claimstaker"

The "Claimstaker" Model DG -5, manufactured by the Detectron Corp., weighs only 1 1/2 pounds and is easy to carry around. Fig. 4-4 shows the instrument being used to check the radioactivity of a rock sample. Simplicity of the circuit can be judged from the schematic diagram, shown in Fig. 4-5.

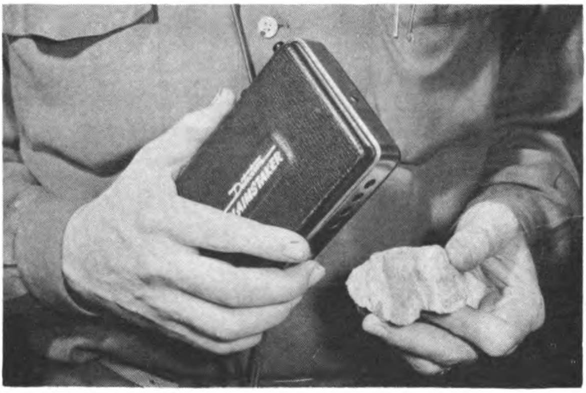


Fig. 4-4. The Detectron Model DG-5 "Claimstaker" Being Used to Check the Radioactivity of a Piece of Ore. Courtesy of The Detection Co.

A novel scheme is used to obtain high voltage (about 900 volts) for operation of the Geiger tube. The battery is connected in series with a push switch and the primary of the transformer. There is a large step-up ratio in the transformer. When you press the switch, current flows through the primary of the transformer, and there is some voltage induced in the secondary. Then when you release the push switch, current halts quickly in the primary, and a larger voltage is induced in the secondary.

The spark gap is the rectifier because it is adjusted so it will discharge with the higher voltage, but will not with the lower voltage. Thus, breakdown occurs for only one polarity, rectifying the transformer output. The spark gap is specially adjusted and treated for this purpose. It has gold electrodes to avoid any corrosion which

would change its characteristics. The .1 mfd capacitor charges up to about 900 volts and holds this charge to apply to the Geiger tube. In Fig. 4-5, the polarity on the capacitor is negative at the top, and positive at the bottom. Geiger tube current is very small, and the

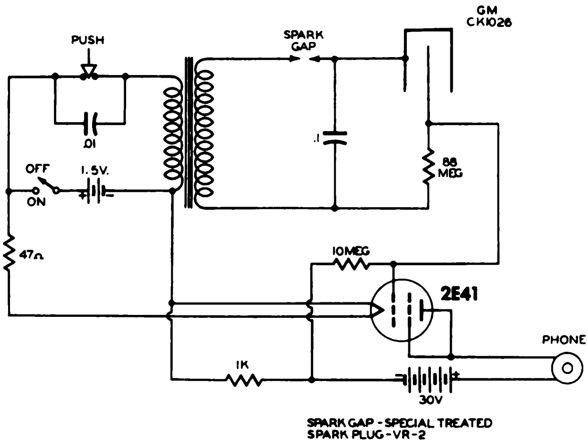


Fig. 4-5. Schematic Diagram of the Detectron "Claimstaker", Model DG-5. Courtesy of The Detectron Company.

capacitor will provide enough voltage to operate the tube for a considerable period of time. When it discharges below the operating potential of the Geiger tube, you restore its voltage by simply pressing and releasing the push button several times. The load resistor for the Geiger tube has a value of 88 megohms.

The Geiger tube has a wall thickness of about 175 mg/cm^2, and will record high-energy beta rays. As can be seen from the photograph, there are holes in the bottom of the case immediately below the Geiger tube so that nothing will interfere with either the beta or gamma rays.

Pulses are amplified by a triode-connected 2E41 operating with a 30-volt plate battery. Loud clicks are produced in the single magnetic headphone which is connected in series with the tube plate and the plate battery. The battery supply used for the transformer also provides filament voltage for the 2E41 through a 47-ohm dropping resistor.

The Goldak "U-238"

The "U-238" Geiger counter manufactured by the Goldak Co. indicates radiation intensity in three different ways: (1) by clicks in the headphone; (2) flashes of the neon light; and (3) the reading on the meter. Weight complete with batteries is less than three pounds.

Holes in the side and bottom of the case permit entry of radiation without attenuation.

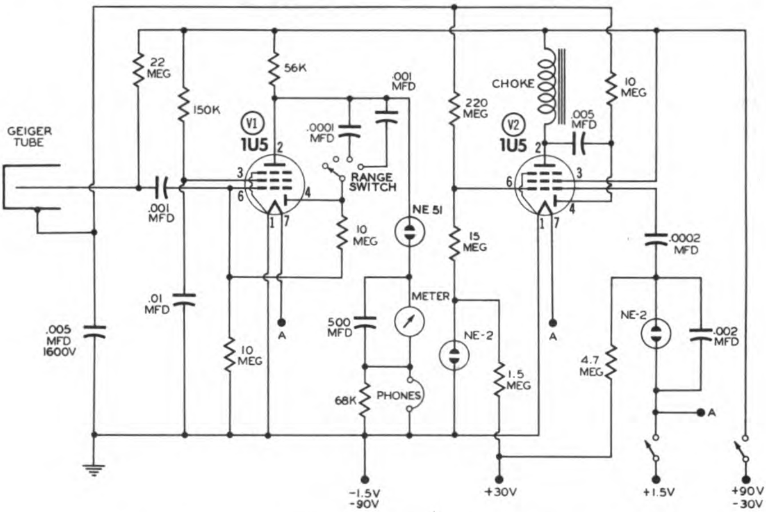


Fig. 4-6. Schematic Diagram of the Goldak Model U-238. Courtesy of the Goldak Co.

Fig. 4-7. The Goldak "U-238" Counter in Use. Courtesy of The Goldak Company.

A rather unusual circuit is used to provide the 900 volts required for the Geiger tube. An NE2 neon tube relaxation oscillator pulses the grid of the right-hand 1U5 (V2 of Fig. 4-6). This pulsing produces rapid changes in current through the choke connected in the

plate circuit. Because of the high inductance of the choke, the changes in current induce a high voltage, which is rectified by the diode portion of the 1U5. A 10 megohm resistor and .005 mfd capacitor filters the high voltage, which is somewhat regulated by an additional NE2 neon tube.

Pulses from the Geiger tube are amplified by a second 1U5 tube (V1). Stability of gain with changing battery voltage is achieved by a feedback arrangement, which also serves as a pulse stretcher so that the negative input signal effectively cuts off the amplifier tube for a long period of time for each pulse. This permits a considerable current in the meter circuit so that a relatively rugged 0-200 microampere meter can be used. Three scales are provided: 0-0.2, 0-2, and 0-20 mr/hr, which is adequate for most uranium prospecting applications and for checking the activity of various ores. The NE51 neon indicator is mounted so that it illuminates the meter face when it flashes.

Although not shown in the photograph of Fig. 4-7, the "U-238" uses printed circuit techniques to reduce size and weight and insure stable operation.

The El-Tronics "Ura-Finder"

A very compact instrument designed specifically for uranium prospecting is shown in Fig. 4-8. It is known as the "Ura-Finder", Model PR-2, and is manufactured by El-Tronics, Inc. An idea of the

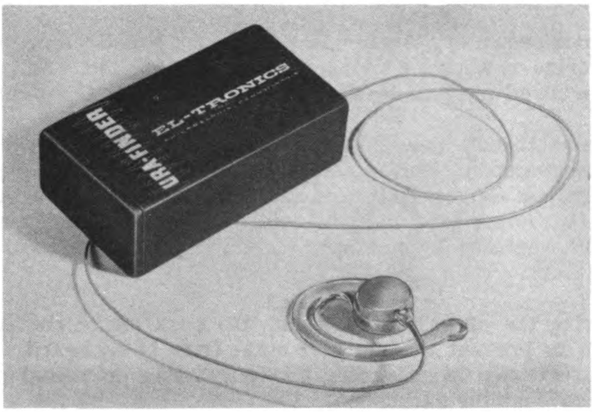


Fig. 4-8. The "Ura-Finder" Pocket Geiger Counter. Courtesy of El-Tronics Inc.

simplicity of this unit can be obtained from an examination of the circuit diagram, Fig. 4-9, which will be used to explain its operation.

When you press the push button, current flows through the relay contacts and the primary of the transformer. It is interrupted by the

series vibrating contacts. The transformer secondary provides a stepped-up voltage to the Geiger tube, the 1 megohm resistor and the .1 mfd capacitor in series. The earphones are shorted out by the pushbutton. The .01 mfd capacitor across the vibrator contacts reduces sparking and burning of the silver contact points.

In this unique circuit, the Geiger tube serves three purposes: first, it is the high voltage rectifier; second, it acts as a voltage regulator; and third, it serves its normal purpose as a radiation-sensitive device. It rectifies because the voltage applied from the

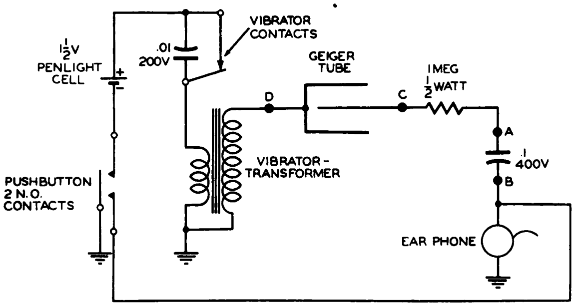


Fig. 4-9. Schematic Diagram of the El-Tronics "Ura-Finder" Geiger Counter, Model PR-2. Courtesy of El-Tronics Inc.

transformer secondary will ionize it when one polarity is applied, but will not ionize it when the reverse polarity is applied. As in instruments discussed previously, the voltage peaks are not symmetrical.

The rectified voltage charges the 0.1 mfd capacitor through the 1 megohm resistor. This potential is equal to the normal operating voltage for the Geiger tube, and has a positive polarity at A in Fig. 4-9. As the Geiger tube operates, this charge is gradually reduced, and can be replaced by pressing the push button again for a short period of time.

During the charging operation, the push button shorts out the earphones to prevent the vibrator noise from being heard. As soon as the push button is released, the Geiger tube operating circuit is complete through the earphones.

Each ionizing event which radiates into the Geiger tube produces a short pulse of current. This flows through the earphones and causes a click. Thus the rate of clicking is a measure of the radiation intensity.

With the instrument responding to only background radiation, the capacitor will remain charged for a relatively long period of time. In a strong field, the counting rate is high and the capacitor discharges more rapidly.

The Geiger tube used in this device is of the halogen-quenched type, as described in Chapter 3. Thus it has a very long life and is not damaged by voltages somewhat in excess of its normal rating. The over-all enclosure is glass, with a thin stainless steel shell serving as the outer electrode, and a stainless steel wire as the inner electrode. Most of the beta rays are screened out by the glass and stainless steel, making the counter sensitive primarily to gamma rays.

Because of its light weight, small size, and small battery requirements, this counter is ideal for taking on hikes, camping trips, and the like where excess weight and bulk can be a burden.

Nuclear-Chicago "Super Sniffer"

The "Super Sniffer" shown in Fig. 4-10 is a general purpose instrument designed for the detection of x-rays, gamma rays, and high-energy beta particles. It appears to be especially well adapted for uranium prospecting. It is small, light in weight, uses standard flashlight cells, and has a battery life of about two hours when operated continuously, or up to six hours total operating time when operated intermittently. A fairly thin wall metal Geiger tube is used which will admit beta rays of high intensity as well as gamma rays.

Fig. 4-10. The Nuclear-Chicago "Super Sniffer". Courtesy of Nuclear Instrument & Chemical Corp.

Operation of the circuit can be explained by referring to the circuit diagram of Fig. 4-11. Placing the switch in the ON position puts 1.5 volts across the vibrator and on the 1U4 filament. Current builds up in the primary of the transformer, and when it reaches a certain value, is interrupted by the vibrator. This sudden interruption causes a large voltage to be built up across the secondary winding. This process is repeated once for every vibrator cycle. The .01 mfd capacitors serve to protect the vibrator contacts.

Rectification of the high-voltage pulses is accomplished by the thyrite resistor, a nonlinear element made by the General Electric Co. This element decreases its resistance with increasing voltage, thus rectifying the nonsymmetrical output of the vibrator transformer. The high voltage applied to the Geiger tube is about 1000 volts. Plate voltage for the 1U4 amplifier tube is obtained from a tap on the thyrite resistor.

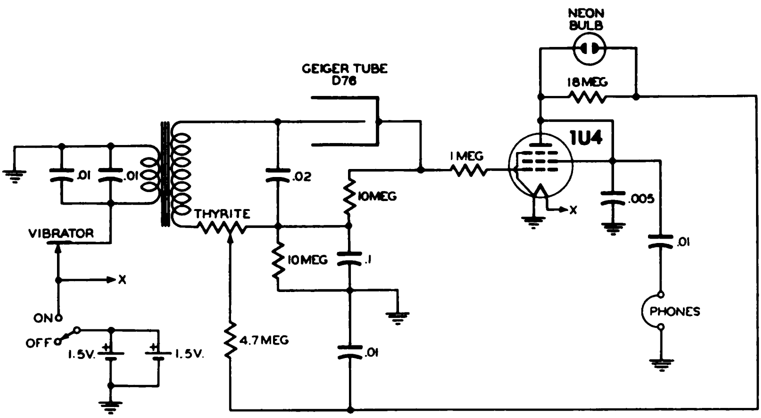


Fig. 4-11. Schematic Diagram of the "Super Sniffer". Made By The Nuclear Instrument & Chemical Corp.

Ionization in the Geiger tube results in a minute current through the 10-megohm resistor in the grid circuit of the 1U4. This current produces a small voltage pulse for each ionizing event, which is amplified by the triode-connected 1U4 amplifier. Each pulse produces a click in the headphones and a flash of the neon bulb. Therefore, intensity of radiation can be judged by the rapidity of clicks or flashes.

The Geiger tube is mounted at the bottom of the case just inside a thin window. This window admits some beta radiation, and permits the instrument to be used for measuring both beta and gamma radiation. The case itself is relatively transparent to gamma rays, so the instrument may be oriented in any desired position when surveying for uranium.

Tracerlab Model SU-5A

The Tracerlab Model SU-5A, shown in Fig. 4-12, is a lightweight, portable, battery operated radioactivity survey and counting-rate meter. The probe, shown fastened to the instrument, includes a Geiger tube having a glass side window with a thickness of approximately 30 mg/cm^2. This permits the detection of gamma and high-energy beta rays above approximately 0.3 mev. A shield with a wall thickness of 1300 mg/cm^2 can be rotated to cover the Geiger tube window, screening out beta rays up to 2.5 mev but still admitting

gammas. A second probe, shown beside the instrument, is equipped with a Geiger tube having a mica end window of less than 2 mg/cm^2, permitting the monitoring of low energy beta rays and alpha rays. The cap shown is a beta shield, screening out all except gamma rays.

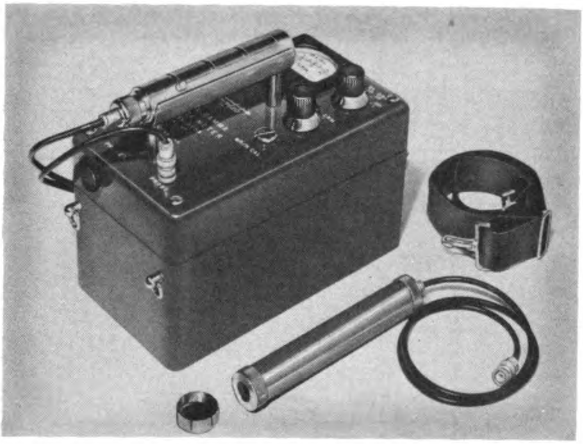


Fig. 4-12. The Tracerlab Model SU-5A with Auxiliary Probe. Courtesy of Tracerlab, Inc.

This instrument incorporates two types of scales — one calibrated in milliroentgens per hour and the other in counts per minute. There are four ranges for each scale — 0.02, 0.2, 2.0 and 20 mr/hr and 100, 1000, 10,000 and 100,000 cpm. The cpm ranges are useful for determining the total number of pulses per minute, while the mr/hr ranges are calibrated to show radiation intensity. The mr/hr ranges yield an accuracy of ±10% of full scale on all ranges, and the cpm ranges have an accuracy of ±5% of full scale for equi-spaced pulses.

Operation of the instrument can best be described by referring to the simplified schematic diagram of Fig. 4-13. The 900-volt potential for the Geiger tube is provided by three 300-volt batteries connected in series. A low value of load resistor (470,000 ohms) is used for R1.

Pulses developed across R1 are coupled to the grid of the pulse amplifier tube V1 (a Raytheon subminiature type CK522AX) through a 50 mmf coupling capacitor, C1. These pulses are negative, and drive V1 to cutoff, resulting in a rapid rise in its plate potential. This pulse in turn is applied to the grid of V2 (also a CK522AX) through C3 (from 50 mmf to 0.047 mfd depending on the range), causing V2 to conduct. This current, flowing through the common cathode resistor R8, 47,000 ohms, keeps V1 practically at cutoff. Capacitor C3 starts to discharge through R4 and R9, resulting in a decrease in the positive bias on V2. This decreases the current in V2 and also

the bias on both tubes. Eventually the bias decreases sufficiently so that V1 again starts to conduct, cutting off V2 and restoring the original conditions. The circuit is, essentially, a one-shot multivibrator.

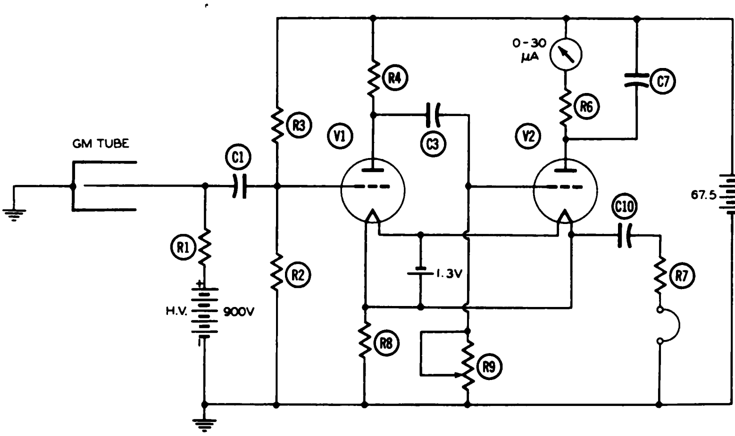


Fig. 4-13. Simplified Circuit Diagram of the Tracerlab Model SU-5A Counter. Courtesy of Tracerlab, Inc.

During the time that V2 is conducting, capacitor C7 is charging. Between pulses, C7 discharges through the 0-30 microampere meter, and through R6. The time constant of this circuit is long compared with the time interval between pulses, so the meter will tend to give an average indication of pulse repetition rate.

Calibration is effected by varying R9 and/or C3 which determines the pulse width and hence the charge per pulse delivered. Values of C3 are 50, 250, 2500, and 47,000 mmf for the four ranges, with a separate 1 megohm potentiometer being provided for each range for R9. Different values of C7 are also provided for different ranges. Headphones may be used for an audible indication of the counting rate.

Plate voltage for the two amplifier tubes is supplied by a single 67 1/2-volt battery, and filament voltage by four 1. 34 volt mercury cells in parallel. The mercury cells and plate battery have a normal operating life of about 240 hours, and the high-voltage batteries about one year.

Tracerlab Model SU-1E

An instrument using an ionization chamber as the sensing element, the Tracerlab Model SU-1E, is shown in Fig. 4-14. It is called the Model SU-1E portable radiation survey meter and is intended for use in so-called "hot" laboratories handling radioactivity of the order of millicuries. Full scale ranges of 15, 150 and 1500

mr/hr have been provided. The currently accepted "tolerance" dosage rate, 7.5 mr/hr, falls exactly at midscale on the lowest range.

The ionization chamber is made of bakelite, coated inside with aquadag to form a conducting layer. An end window of very thin pliofilm (about 2-3 mg/cm^2) is provided to permit the entry of beta particles having energies as low as 0.1 mev. A shutter is included to

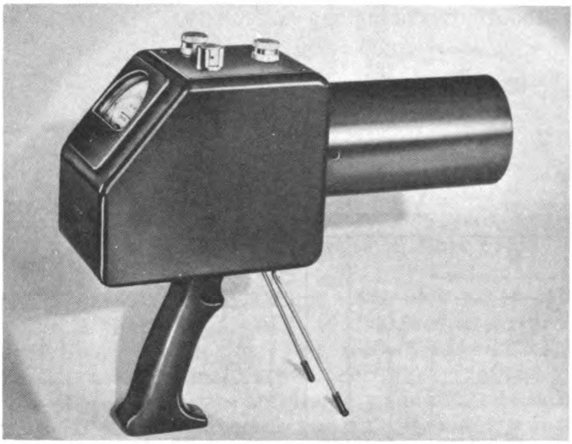


Fig. 4-14. The Tracerlab Model SU-1E.
Courtesy of Tracerlab, Incorporated.

screen out all beta radiation, if desired, and permit reading of only the gamma ray component. Chamber volume is selected to give adequate ionization current for the range of intensities to be measured. The effective volume is 400 cubic centimeters which yields a current of 10^{-12} ampere when irradiated by a field of 25 mr/hr. Chamber voltage is 60 volts, supplied by batteries.

The various ranges are provided by switching-in various load resistors for the chamber. For the most sensitive range, 15 mr/hr, the load resistor is 5×10^{12} ohms (5 million megohms); for the 150 mr/hr range, 5.5×10^{11} ohms, and for the 1500 mr/hr range, 5×10^{10} ohms. Because of these extremely high values, great care is taken in the design and assembly of components to eliminate leakage resistance as far as possible.

The output across the load resistor is not sufficient to conveniently drive a meter, so an amplifier is included, consisting of a voltage amplifier stage and a cathode follower stage. Over-all gain, with both positive and negative feedback, is about 70, which is sufficient to drive a 0-100 microampere meter. Because of the negative feedback, the instrument will hold its calibration throughout battery and tube life. Replacing tubes does not alter the calibration, but the manufacturer does not recommend changing tubes because of the

danger of getting oil or dirt on parts where leakage resistance must be made negligible. It is recommended that the instrument be returned to the factory for tube replacement.

Subminiature tubes are used in the amplifier. The voltage amplifier is a tetrode-connected CK571AX which is directly coupled to the grid of the cathode follower power output tube, a CK526AX. Plate voltage for the CK571AX is derived from the screen voltage of the CK526AX, resulting in controlled positive feedback. Thus the gain is increased without introducing any instability.

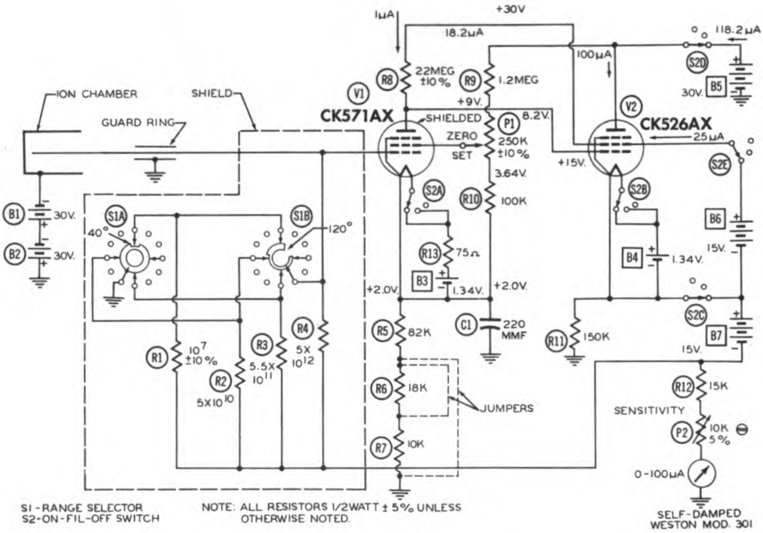


Fig. 4-15. Schematic Diagram of Tracerlab Model SU-1E. Courtesy of Tracerlab, Inc.

As can be seen from the circuit diagram of Fig. 4-15, the inverse feedback consists of a loop from the meter circuit back to the grid of the input stage. The meter is self-damped, and reaches its full reading in about 1.5 seconds on all ranges.

Battery complement for this instrument consists of three 30-volt and two 15-volt units, together with two 1.34-volt mercury cells. The circuit has been so designed that all batteries will have a life of about 800 operating hours, making it convenient to replace all batteries at once.

Orlokator, Jr., Nucleonic Co. of America

Designed primarily for prospecting and assaying, the Orlokator, Jr., manufactured by the Nucleonic Company of America, is a lightweight instrument for the detection of high-energy beta rays and

gamma rays (see Fig. 4-16). The presence of radiation is indicated by a flashing light and a clicking sound in the headphones.

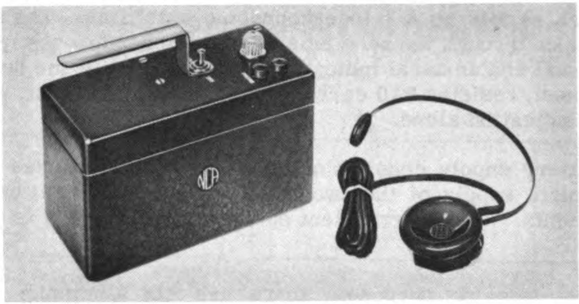


Fig. 4-16. The "Orlokator, Jr". Courtesy of Nucleonic Company of America

High voltage for the Geiger tube (900 v.) is provided by a special circuit (Fig. 4-17) which is designed to produce a constant output voltage over a wide range of battery voltages. R1, C1, and the neon tube V1 constitute a relaxation oscillator. Voltage across V1 is a sawtooth of about 10 volts amplitude. The differentiating action of C2 and R3 modifies this sawtooth into an unsymmetrical square wave

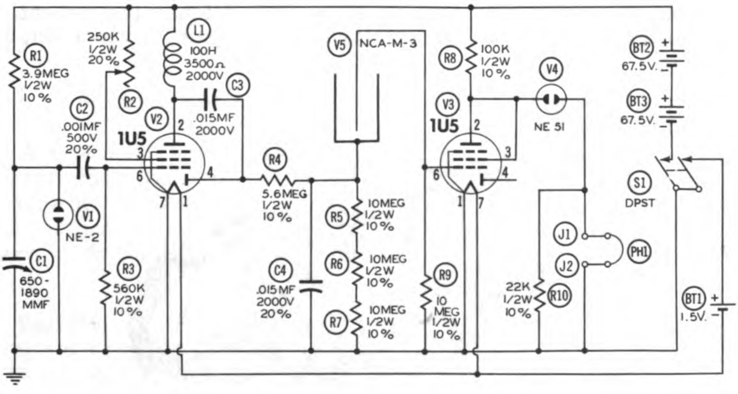


Fig. 4-17. Schematic Diagram of the Orlokator, Jr. Model RD, Made By the Nucleonic Company of America.

on the grid of V2, a 1U5 tube. V2 then acts as a switch, switching the current through a very high inductance, L1, on and off, generating a high voltage pulse. This pulse is rectified by the diode portion of V2, filtered by R4 and C4, and impressed on the Geiger tube. Proper adjustment of R2, the 1U5 screen resistor, and C1 results in the

correct output voltage with extremely good regulation as the battery voltage varies.

Pulses from the Geiger tube are directed to the grid of a second 1U5 which serves as a triode-connected amplifier. The amplified pulses pass through the neon tube V4 and the headphones, producing both a visual and an aural indication of the pulses. If the headphones are not used, resistor R10 carries the neon lamp current, producing a visual indication alone.

Battery supply consists of two 67 1/2-volt batteries in series for the plate supply of the two tubes, and a 1 1/2-volt battery for the filaments. With intermittent operation, battery life is about 150 hours.

For assaying purposes, there are six aluminum planchets which are furnished with the instrument. Five of these are filled with ore samples with known uranium content. They are identified with the ore concentration. The sixth planchet can then be filled with ore of unknown concentration, and its content approximated by comparison with the other samples. Comparison is obtained by counting the readings (clicks or flashes per minute) for each of the planchets.

El-Tronics "Rad-Tek" Model SID-1

The "Rad-Tek" Model SID-1, manufactured by El-Tronics, Inc. was designed especially for use as a civil defense instrument. It uses an air ionization chamber for detecting gamma radiation, and

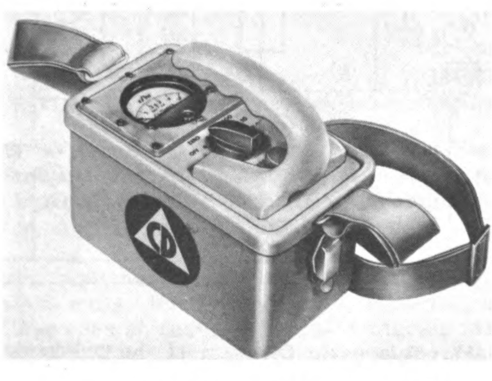
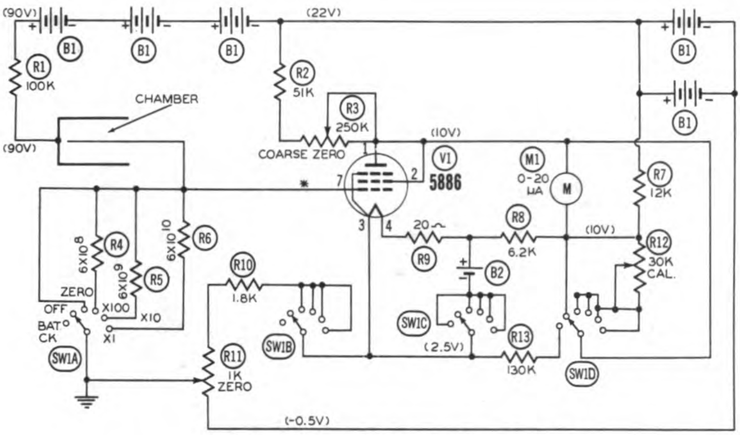


Fig. 4-18. The "Rad-Tek" Model SID-1. Courtesy of El-Tronics, Inc.

incorporates a meter for direct reading of the rate at which radiation is being received. The instrument, shown in Fig. 4-18, has three ranges: 0-0.5, 0-5, and 0-50 r/hr.

Total potential on the ionization chamber is 90 volts, provided by batteries. The different ranges are obtained by switching in different values for the chamber load resistor. Because of the extremely small current through the chamber even when irradiated at the 50 r/hr rate, these load resistors are large, being 600, 6,000 and 60,000 megohms respectively for the 0-50, 0-5, and 0-0.5 r/hr ranges.



ALL SWITCH POSITIONS GANGED-SHOWN IN THE OFF POSITION

* DO NOT MEASURE GRID CIRCUIT VOLTAGE TUBE MAY BE DAMAGED.

B1-22 1/2 VOLT-EVEREADY-TYPE 412

B2-1 1/2 VOLT-D-CELL

Fig. 4-19. Schematic Diagram of the "Rad-Tek" Model SID-1. Courtesy of El-Tronics, Inc.

A type 5886 electrometer tube is used to amplify the small voltages produced across the load resistors. (See circuit in Fig. 4-19). This tube is connected in a bridge circuit with a 0-20 microampere meter serving as the indicator. Calibration adjustment is provided by varying the meter shunt resistor R12.

Battery requirements for this instrument are five 22 1/2 volt hearing aid batteries and a single Type D 1 1/2 volt flashlight cell. Life of all batteries with continuous operation is over 100 hours.

A novel feature of this instrument is a switch position which permits the 1 1/2 volt flashlight battery to be checked. With the switch in the "battery check" position, the meter should read above the mark at the center of the scale. If the meter reads below this point, the battery should be replaced. The 22 1/2 volt batteries must be checked on a separate meter. When the voltage falls below 18 volts as indicated on the 50 volt scale of a 1000 ohms per volt meter, these should be replaced also.

El-Tronics Model SM-3

This instrument, shown in Fig. 4-20, is a portable, battery-operated survey meter for the detection and measurement of beta and gamma radiation. Radiation intensities are indicated by a direct reading meter calibrated in mr/hr. Three ranges are provided: 0.2, 2.0, and 20 mr/hr full scale, selected by means of a selector switch on the front panel. The same switch disconnects the batteries and renders the instrument inoperative when in the "off" position.

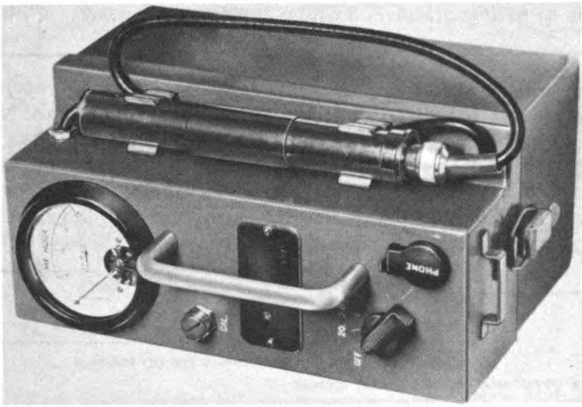


Fig. 4-20. The El-Tronics Model SM-3.
Courtesy of El-Tronics, Incorporated.

A probe is provided which contains a thin-wall counter tube of about 30 mg/cm^2 capable of indicating gamma and strong beta radiation. When it is desired to measure gamma radiation only, a movable shield is positioned so that beta radiation is excluded. The wall of the counter tube permits the passage of 25% of the beta ray spectrum where the maximum intensity is 350 kev.

High voltage (900 volts) for the Geiger tube is supplied by three special 300 volt batteries connected in series (see circuit in Fig. 4-21). A low value of load resistor R1 (2.2 megohms) gives sharp pulses which are fed to the grid of the 1U5 amplifier tube. Amplified pulses are thus formed across the 120,000 ohm plate load resistor R5. In the two less sensitive positions, these pulses are connected to the diode of the 1U5 tube through C1 and C2 respectively. The negative DC pulses resulting from this rectifier action are larger in magnitude than the original pulses from the counter tube, and since they arrive within the duration of the original input pulse, they can be used to amplify the grid pulses. The degree of amplification depends on the values of C1 and C2.

The integrating circuit used for meter indication requires pulses having substantially constant amplitude and width. A special

neon tube in the plate circuit of the first amplifier accomplishes this equalization. With V1 conducting, the voltage across the NE51 is not sufficient to produce breakdown. However, when a negative input cuts off V1, the voltage rises, causing the NE51 to breakdown. Since the voltage across the NE51 is substantially constant after breakdown, substantially equal pulses will be formed for each ionizing event.

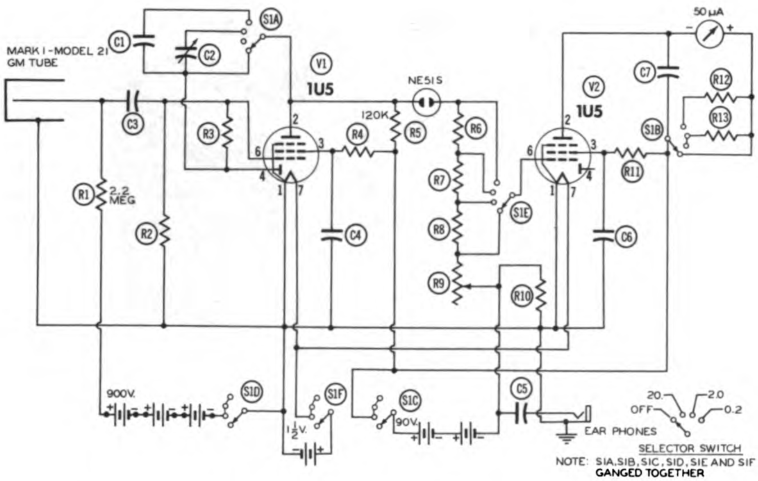


Fig. 4-21. Schematic Diagram of the El-Tronics Model SM-3. Courtesy of El-Tronics, Incorporated.

The voltage divider consisting of R6, R7, R8, and R9 is connected to the grid of the 1U5 integrating tube by means of the range switch. Pulses of current in the plate circuit are smoothed out and indicated by the 0-50 microampere meter which is calibrated to read radiation intensity. Calibration of the high range automatically results in correct calibration of the other ranges because resistors R6, R7, R8, R12, R13, and capacitors C1 and C2 are properly selected at the time of manufacture. Over-all accuracy on all three ranges is better than 10% of full scale. An outlet for high-impedance headphones is included for use when the radiation intensity is too weak to read on the lowest scale.

Berkeley Model 2750

This radiation meter is designed to measure and detect beta, gamma, and x-rays. It is ideally suited for mineralogical surveys, civil defense needs, decontamination work, and tracking tracer elements (see Fig. 4-22). A self-quenching Geiger tube is located in a probe at the end of a 3-ft. cable. Full-scale ranges of 0.2, 2.0, and 20 mr/hr are provided by means of a switch on the front panel, which also has "off" and "check" positions.

The Geiger tube has a glass wall thickness of 30 mg/cm^2, and a polyethylene shield in the probe makes a total thickness of 50 mg/cm^2. Thus, some high-energy beta rays are admitted. The perforated area of the probe is 60% of the total area.

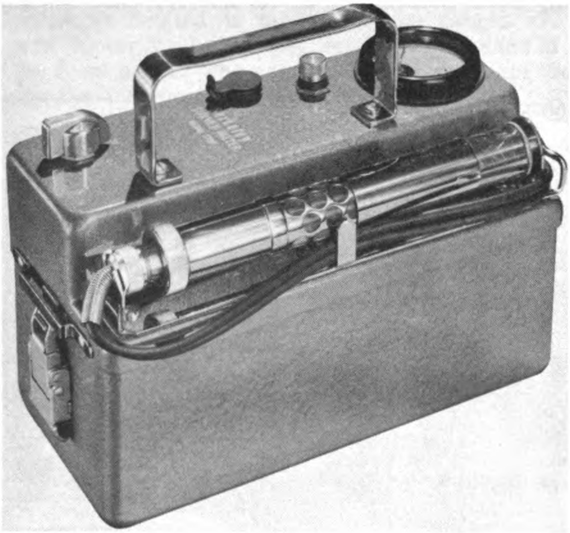


Fig. 4-22. The Berkeley Model 2750. Courtesy of Berkeley Division, Beckman Instruments, Inc.

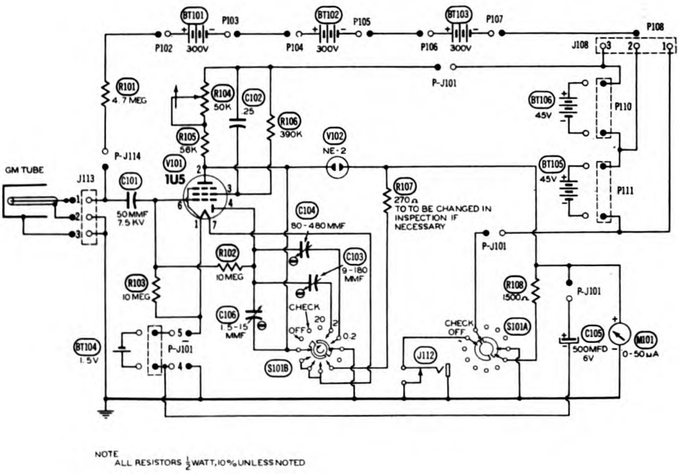


Fig. 4-23. Schematic of the Berkeley Model 2750. Courtesy of Berkeley Division, Beckman Instruments, Inc.

Three 300-volt batteries connected in series give the 900 volts required for Geiger tube operation (see Fig. 4-23). Two 45-volt batteries in series provide 90 volts for plate voltage on the 1U5 amplifier tube. One or both of these batteries may be connected in series with the 900-volt supply to give a Geiger tube voltage of 945 or 990 volts. A single 1.5-volt battery powers the filament of the 1U5 tube.

Pulses from the Geiger tube are negative, and cut off the plate current of the 1U5. This causes the plate voltage to rise, firing the neon tube NE2. A part of the current through NE2 is shunted through the 0-50 microampere meter indicating the strength of radiation. Meanwhile, the appropriate calibrating capacitor has been charged through the diode section of V101. When the NE2 begins to conduct, the calibrating capacitor discharges through R102 and R103, biasing the 1U5 below cut-off for a period depending on the time constant of the circuit. When the capacitor is discharged, current starts to flow in the 1U5, reducing the plate voltage and extinguishing the NE2.

The meter is properly damped on each range so that individual pulses of current in effect produce an integrated reading. The 500 mfd capacitor used on the lowest range must have a leakage resistance of at least 50,000 ohms to maintain calibration.

In the "check" position on the switch, filament voltage is removed from the 1U5, and R107 is connected in parallel with the meter. R104 is then adjusted for full-scale deflection. This adjustment permits calibration to be maintained over a wide range of battery voltages for the 45-volt batteries.

Provision is made for using headphones if desired. When in use, the phones are in series with the negative plate battery supply. When not in use, the circuit continuity is maintained by a closed-circuit jack.

Anton Radiac Set

A versatile counter designed for the Navy, called Radiac Set AN/PDR-32 (XN-3), is manufactured by Anton Electronic Labs. (See Fig. 4-24). It is a rugged, miniaturized portable unit which will measure gamma radiation over the range of 0.005 to 500 r/hr on a single scale, and is capable of indicating beta radiation alone or in the presence of gamma rays.

Two specially designed Geiger tubes are used to cover the extremely wide range of the instrument. These are connected in parallel to the indicating circuit, so no switching is necessary. (See circuit in Fig. 4-25). The counter tubes are called integrator tubes, as they are designed to handle currents much larger than conventional Geiger tubes. Both the cathode and anode of an integrator tube are specially processed during manufacture, and the tube is capable of passing sufficient current to be read on a rugged, portable meter without additional amplification. Each of the integrator tubes has a

thin mica end window for admitting beta rays. Diameter of this window is about .090 inches. Provision is made in the instrument for a shutter to screen out beta rays if desired.

The high-voltage supply provides two separate channels of regulated DC power, each of which may be varied over a minimum

Fig. 4-24. Two Views of the Radiac Set AN/PDR-32 (XN-3) with Accessories. Courtesy of Anton Electronic Labs.

range of 645 to 705 volts by means of corona-discharge variable-voltage regulator tubes. The power supply operates on the vibrator-interrupter principle, which converts the 3-volt battery source to a high voltage. Rectification takes place in a CK-1036 cold-cathode rectifier.

Ionizing events cause current to flow through one or both of the integrator tubes, and through the 56,000-ohm headset load resistor R106 and the integrating capacitor C103. The AC component of the current is passed on to the headset to give an aural indication. The pulsating DC charges C103 to a value depending on the average radiation level.

A chopper contact is provided on the power supply vibrator which periodically discharges C103 through the primary of the meter transformer, T102. An alternating current is induced in the secondary which is rectified by a 1N56 crystal and applied to a special 0-500

microampere DC meter. Thus the meter scale can be calibrated directly in roentgens per hour. The scale is logarithmic.

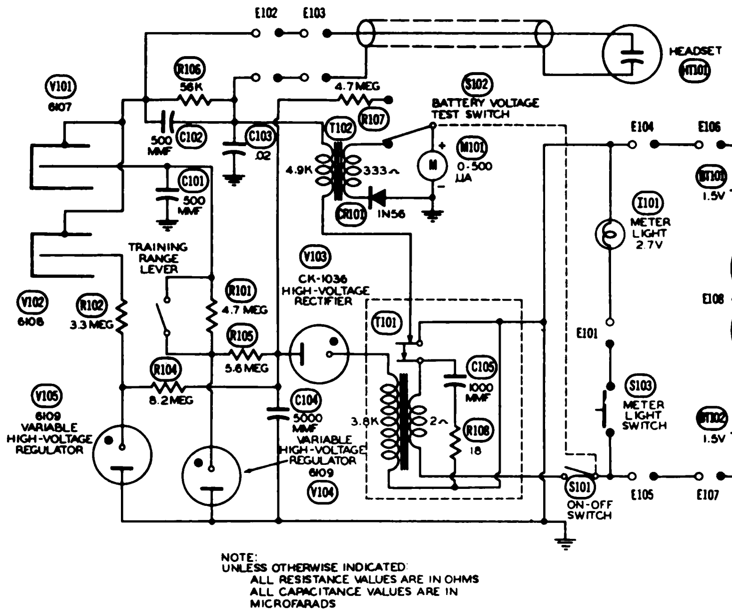


Fig. 4-25. Schematic Diagram of the Radiac Set AN/PDR-32 (XN-3). Courtesy of Anton Electronic Labs.

Battery voltage and vibrator operation are checked simultaneously. In the "test" position of the switch, the meter is connected to the output of the high voltage rectifier through a 4.7 megohm resistor, R107. If the meter reads below a previously calibrated mark on the dial, the batteries should be replaced.

Norelco Model PW 4010

This small, light-weight counter (Fig. 4-26) is available from the North American Philips Co. It is discussed here primarily because of its novel battery-saving circuit. A partial schematic only, without a parts list, is presented in Fig. 4-27 because this is sufficient to explain the circuit operation.

The novel feature of this unit is the fact that high voltage for the counter tube is generated only when a count is actually taking place, thus greatly reducing demands on the batteries. High voltage for the halogen-quenched Geiger tube (type 18502 operating at 350 volts) is obtained from a special diode-pentode oscillator tube, a

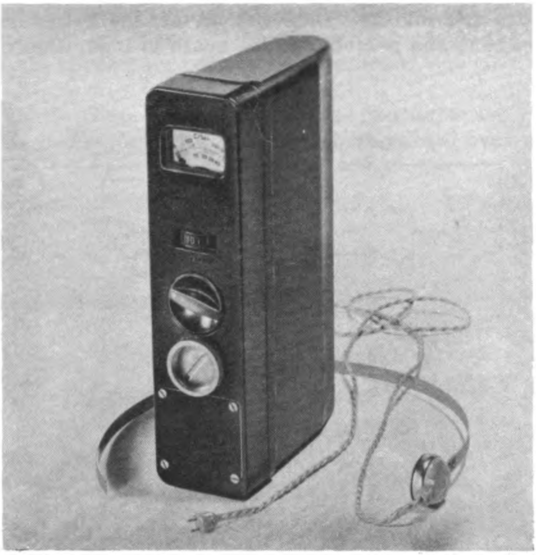


Fig. 4-26. The Norelco Model PW 4010 Radiation Detector. Courtesy of North American Philips Co., Inc.

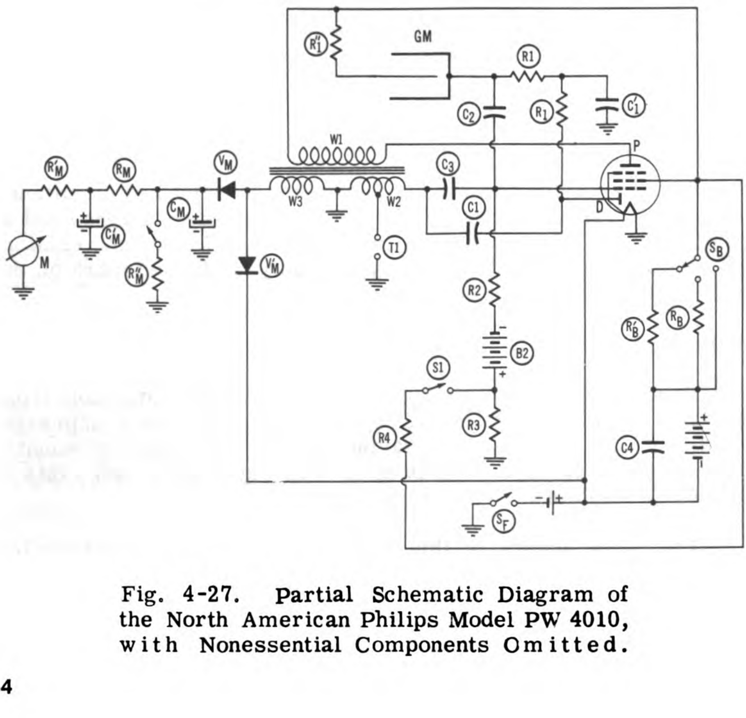


Fig. 4-27. Partial Schematic Diagram of the North American Philips Model PW 4010, with Nonessential Components Omitted.

type 95106. Oscillations in this tube are rectified in the diode section to produce the high voltage. The tube is normally biased beyond cut-off, this bias being overcome whenever the Geiger tube conducts.

Thus, the pentode oscillator draws plate current only during the very short space of time that a pulse is being received. Such operation prolongs the life of the plate batteries.

Capacitor C1 serves as the storage capacitor for the Geiger tube. In order for the unit to start operating, this capacitor must be originally charged to 350 v. To accomplish this, switch S1 is provided which serves to remove the bias on the grid of the oscillator tube, permitting it to oscillate and charge up the capacitor. In actual practice, this switch need be closed only a very short time for C1 to be charged to its full potential of 350 v. When turning the instrument on, a momentary switch position is provided which automatically carries out this operation, thus requiring no special attention on the part of the operator.

A separate winding (W3) on the oscillator transformer serves to drive the indicating meter M. Because of this arrangement, voltage is fed to the meter circuit at the same time that oscillations take place. Maximum use is made of all available power from the oscillator to minimize battery drain. The various resistors and capacitors in the meter circuit provide proper damping for the two ranges, 0-40 and 0-800 cpm, which correspond approximately to 0-1.25 and 0-25 mr/hr. Headphones may be connected between the terminals marked "T1" if aural indications are desired.

The Geiger tube has a wall thickness of 75 mg/cm^2, and the case has approximately the same thickness. Thus, all alpha rays and low energy beta rays are screened out, making the instrument sensitive to medium energy beta rays, gamma rays, and x-rays.

Total weight of the unit, including two special 30-volt batteries and a 1.5-volt penlite cell is about 1 lb. 9 3/4 oz. Outside dimensions of the case are 5 5/8" x 1 5/8" x 4 1/8". Two positions on the selector switch indicate plate and filament battery condition. The single earphone shown with the unit weighs only 1 1/32 oz.

Hoffman Laboratories "Countmaster"

A new approach to the design of a radiation-detection instrument is incorporated in the Hoffman "Countmaster" shown in Fig. 4-28. An automatic timer and digital counter are included, interconnected in such a manner that the exact number of counts for a given period of time (up to two minutes) can be determined directly from the bank of neon lamps on the face of the instrument. This permits much more accurate surveys than is possible with a meter indication alone.

The Geiger tube is mounted in a probe which can be clamped in place or can be removed. A sliding shield in the probe may be closed to shield out all beta rays, or opened to permit measurement

of the stronger betas. For survey work, the probe can be left clamped in place but can be removed for contamination measurements or assaying.

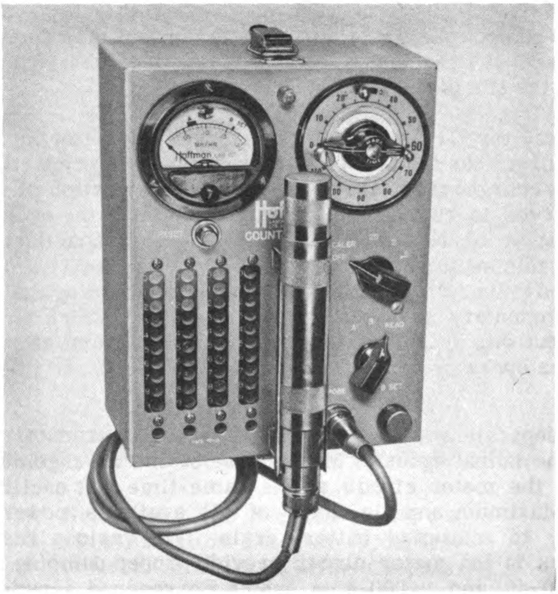


Fig. 4-28. The Hoffman "Countmaster".
Courtesy of Hoffman Laboratories.

A block diagram of the instrument (Fig. 4-29) indicates the basic operating principles. High voltage for the Geiger tube (900 volts) is obtained from a battery-operated regulated supply. Output pulses are fed to a pulse shaper and multivibrator, and then to the meter indicating circuit. The output of the multivibrator is also fed to the automatic timer and digital counter circuit.

The function of the automatic timer is to close the circuit to the neon diode ring digital counter for a certain predetermined time, for example, one minute. The counter then indicates the number of counts received during this interval. A reset button is provided to return the count for the digital counter to zero when desired.

Front panel controls include two switches, as can be seen in the photograph. The upper switch has an "off" position, a "scaler" position for connecting the digital counter, and three meter range positions: 0-.2, 0-2, and 0-20 mr/hr. The lower switch has two positions for checking battery voltage and one position for normal operation.

Battery complement consists of two 75-volt "B" batteries, one 15-volt "B" battery, and 4 standard 1 1/2-volt flashlight batteries.

Normal life of the "B" batteries is 65 hours when used 6 hours per day in the scaler position, or 200 hours in the meter position. Life of the flashlight cells is about 65 hours, and of the 15-volt "B" battery is shelf life (8-12 months). Total weight of the unit is 7 1/4 lbs.

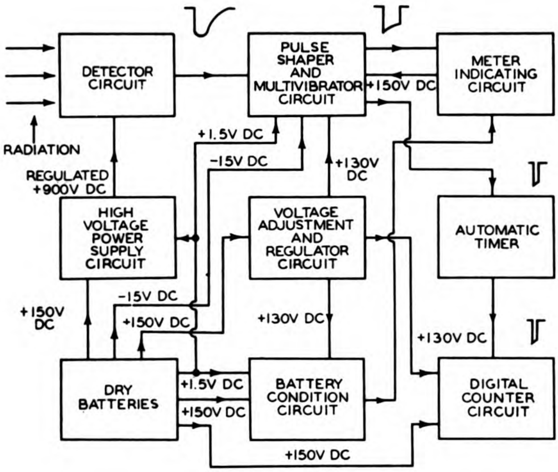


Fig. 4-29. Block Diagram of "Countmaster". Courtesy of Hoffman Laboratories.

Radiac "Nucliometer"

An unusual counter which deserves mention is the Nucliometer, sold by the Radiac Co,, Inc. It is a new type of multiple Geiger tube

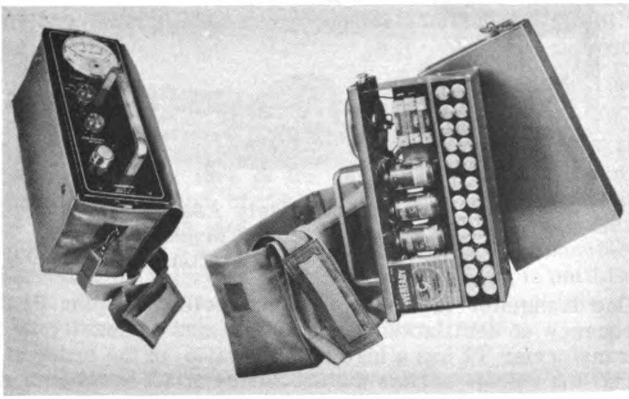


Fig. 4-30. The Radiac "Nucliometer". Courtesy of The Radiac Company, Inc.

count rate meter for radioactivity detection where extreme sensitivity is required.

The novel feature of this instrument is the fact that it contains twenty-four Geiger tubes connected in parallel, to increase the sensitivity. These tubes can be seen in the photograph of Fig. 4-30. According to the manufacturer, the extreme sensitivity achieved in the Nucliometer makes it most applicable for locating deeply-buried deposits of uranium, oil-bearing stratigraphic traps, and the like. It can be used for prospecting from a low-flying airplane, a moving vehicle, or on foot.

Bismuth coated Geiger tubes may be used to further increase the sensitivity by a factor of 2 to 5. A meter indicates counts per minute, and a time-constant switch permits selection of time constants from 2 to 16 seconds. A compensator permits the meter to be set to zero to balance out the background radiation in any particular area.

Transistor Geiger Kit

A Geiger counter which uses two transistors in its circuit is sold in kit form by J. Young and Company. The complete unit is shown in Fig. 4-31, and a schematic diagram in Fig. 4-32.

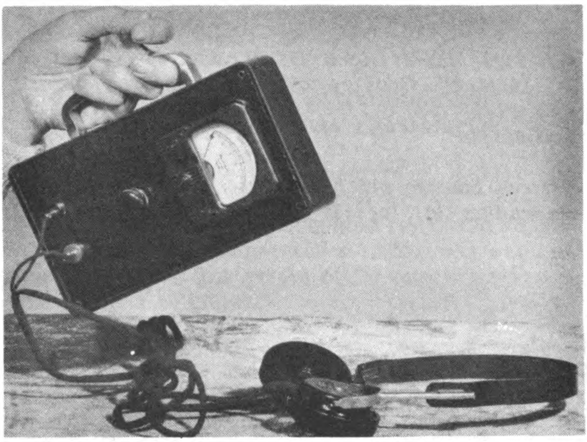


Fig. 4-31. Completely Assembled Transistor Geiger Counter Model K-1. Courtesy of J. Young & Company.

One transistor is employed as an oscillator in the V1 circuit, the frequency of oscillation being determined primarily by R1 and C1. Transformer T2 has a high step-up ratio, of the order of 400 to 1, so that the voltage across the secondary of T2 is very high. This voltage is rectified by a selenium rectifier, and filtered by C2. The neon bulb and 30 megohm resistor R3 serve to regulate the voltage to about 450 volts, the value required for the Geiger tube.

Pulses from the Geiger tube are transmitted to the second transistor, V2, through transformer T1, where they are amplified and indicated on the 0-200 microampere meter M. Capacitor C5 (500 mfd) serves to smooth out the pulses to give a reasonably steady meter reading. T1 has a step-down ratio of 80 to 1 to match the impedance of the Geiger tube to the transistor . Headphones may also be used as indicated.

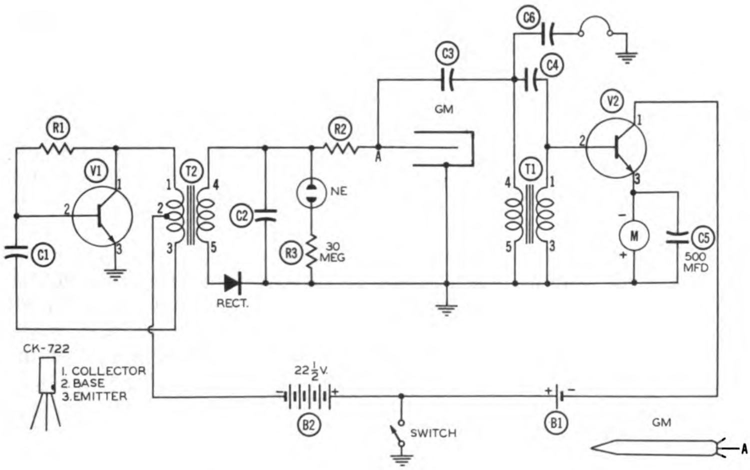


Fig. 4-32. Schematic Diagram of Geiger Counter Kit Using Two Transistors.

The batteries consist of a mercury cell (B1) and a 22 1/2-volt hearing aid battery (B2). Life of B1 is about 200 hours, and that of B2 about 100 hours. A halogen-quenched Geiger tube provides exceptionally long life and high output. Full-scale sensitivity is 2 mr/hr, permitting the detection of small amounts of radioactivity.

Future Developments

A study of the various instruments described in this chapter will give an excellent idea of the current practice followed in the design and construction of Geiger counters now on the market. However, new designs are appearing regularly. Because of the highly competitive nature of this branch of electronics, manufacturers are understandably reluctant to disclose latest designs until they are actually on the market. For this reason, we can talk only in generalities when discussing possible future trends.

It is obvious that many new designs will make extensive use of printed circuits. Printed circuit techniques have reached the stage where they can be and are being used competitively with other assembly methods. Advantages are numerous, including lighter

weight, reduced assembly time, smaller size, and greater reliability. These techniques have already found wide application in the radio and television industry and in military electronics production, and several Geiger counters now on the market employ such construction.

Much has been said about transistors in recent years. A great deal of experimental work is now being carried on to adapt transistors to Geiger counters, and many commercial instruments of the future will be designed around them. Their advantages are many — reduced weight and size, reduced battery consumption, longer life, and greater ruggedness. They are ideally suited for the amplifier stages in a counter, and can be used as oscillators to generate the necessary high voltage for the counter tube. The inherent current gain in a transistor will permit counter designs using less sensitive and more rugged meters. Continued improvement and price reductions in the transistors themselves will help to accelerate their applications to counters.

Improvements are also being made in Geiger tubes. Probably the most significant development in this field has been the halogen-quenched tube, which has several advantages over the organically-quenched type. Greater sensitivity to gamma radiation may be achieved by the use of different materials for the envelope or inner coating. Perhaps tubes will be developed which will operate at voltages considerably below the 300 volt minimum of presently-available types.

The Geiger counter industry has had a period of dynamic growth in the last few years, and it can be expected that this growth will continue.

CHAPTER 5

Scintillation Counters

In Chapter 3, it was shown that certain materials will give off flashes of light when they are affected by atomic radiation. The process is called scintillation. This basic principle is utilized in the commercial scintillation counters and detectors which are now on the market.

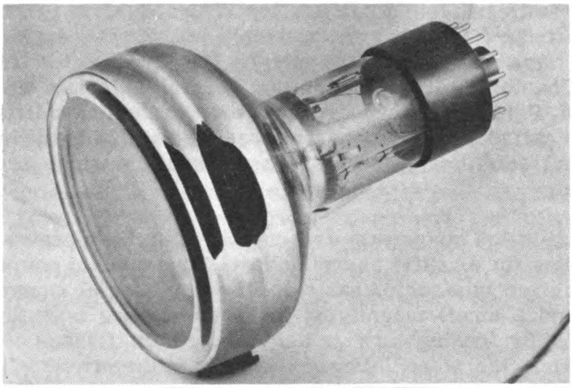
Scintillation detectors are simple and inexpensive devices, some selling for as little as one dollar. They consist primarily of a small enclosed tube which has scintillating material mounted inside one end and a small magnifying lens and viewing hole through the other end. By looking through the viewing hole, flashes of light can be seen when the scintillating material is in the presence of atomic radiation. The number of flashes per unit time indicates the relative intensity of radiation.

The scintillating material can be any of the commonly available materials mentioned in Chapter 3, or it can be a thin layer of flourescent material similar to that which is applied to the inside face of a television picture tube. The operator's eye must become dark-adjusted before he can see the flashes, and it is necessary to count the flashes for a known period of time to compare varying radiation intensities.

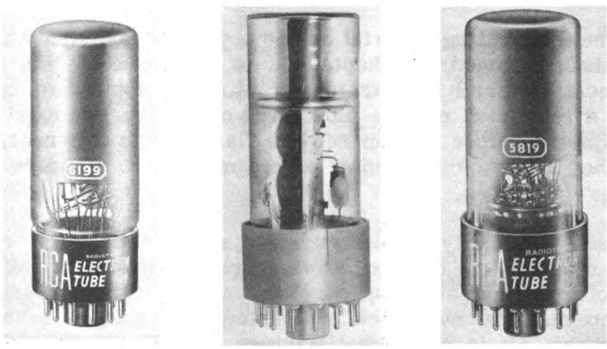
Such simplicity necessarily limits applications. A radiating source close to the detector can produce satisfactory indications. Pieces of rock which are suspected of containing uranium, or clothing or other material suspected of contamination can be examined at close range. It is not as satisfactory for general prospecting or surveying.

In commercial scintillation counters, the flashes of light are "seen" by a photoelectric tube which creates an electrical impulse for each flash. Then the impulses are amplified and counted. The type of tube which is most commonly used for this purpose is the photomultiplier; it has an extremely high sensitivity when it is connected and operated properly.

The photomultiplier tube consists essentially of a photocathode, a series of dynodes, and an anode. When light strikes the photocathode, electrons are given off. These electrons are accelerated towards the first dynode and focused so that none are lost. Each dynode is made of a material having high secondary emission, so that every electron striking it causes several electrons to be given off. These new electrons are then accelerated and focused towards the second dynode, where a similar action takes place. By the time the anode is reached, there may be as many as two million electrons for every electron given off by the photocathode. Thus the tube produces an amplification of up to two million. As a result, the tube is very sensitive, that is, it will respond to extremely small flashes of light.



DuMont 6364 (5" face)



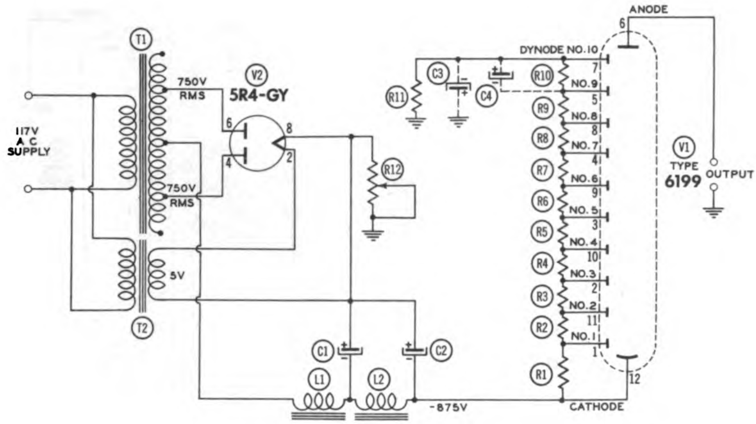
RCA 6199 DuMont 6292 RCA 5819

Fig. 5-1. Several Photomultiplier Tubes.

A group of typical photomultiplier tubes is shown in Fig. 5-1. All are of the end-window type; that is, they are sensitive to light coming into the end of the tube. In practice, the scintillating crystal is mounted against the end of the tube, or against a "light pipe", a piece of lucite, which in turn is mounted against the end of the tube.

Sometimes a silicone oil or grease is used to couple the lucite or crystal to the photomultiplier window.

To provide focusing and acceleration, each dynode of the photomultiplier is connected to a successively higher DC potential. The potential difference between individual dynodes is usually of the order of 100-125 volts, so the total voltage required is 900-1200 volts.



PARTS LIST

C1, C2 - 2MFD, 1000V
C3, C4-8MFD 150V. Required only if high peak currents are drawn.
L1, L2 - United Transformer Corp. No. R-17, or equivalent
R1 - 39K ohms, 2 watts
R2, R3, R4, R5, R6, R7, R8, R9, R10 - 18K ohms, 1 watt
R11 - 12K ohms, 1 watt
R12 - 200K ohms, 12watt adjustable (General Radio Type 471-A, or equivalent)
T1-United Transformer Corp. No. S-45, or equivalent.
T2-United Transformer Corp. No. FT-6, or equivalent.

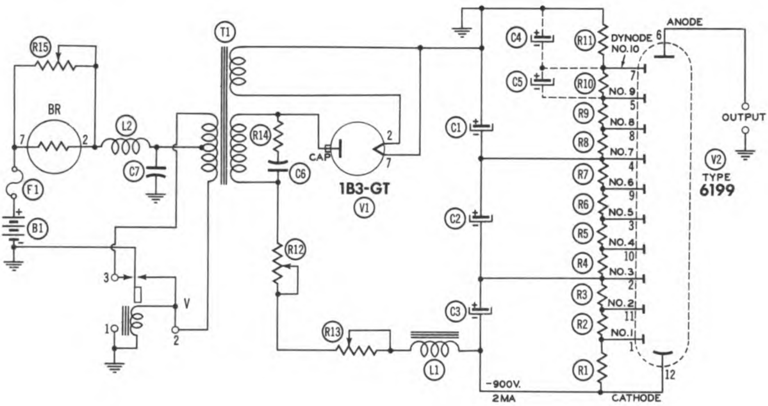
Fig. 5-2. Full-Wave Rectifier Power-Supply Circuit with Voltage Divider for Supplying DC Voltages to RCA Type 5819 in Applications Critical as to Hum Modulation. Courtesy of Radio Corporation of America.

Only a very small current is required, however, which simplifies the power supply problem. Several methods are available for obtaining this high voltage at low currents. Figs. 5-2 and 5-3 show circuits suggested by RCA, the first for AC operation and the second for use with a DC source of 5.5 to 7.5 volts, such as a storage battery or dry cells. Voltage for the various dynodes is obtained by means of a voltage divider.

Streams of electrons, such as exist in photomultiplier tubes, are very sensitive to stray magnetic fields. Therefore, in practice,

the tubes are carefully shielded with mu metal or other suitable material to overcome the effects of the earth's magnetic field or any other stray fields in the vicinity.

Electrostatic shielding is also necessary, since relatively small stray electrostatic fields could disrupt the focusing action of the various dynodes.



B - 5.5 to 7.5 volts, battery consisting of 3 Willard type 25-2 cells, or equivalent.
BR - Ballast Resistor, Amperite type 15-2
C1, C2, C3 - 12MFD, 450 Volts
C4, C5 - 8MFD, 150 Volts, Required only if high peak currents are drawn.
C6 - .003MFD ±10%, oil-filled, 1600 volts, Mallory type PT-1623 or equivalent.
C7 - .5MFD 50 volts, Mallory type RF-481, or equivalent
L1 - Choke, 70 henries, 1850 ohms DC, Thordarson type T20C51, or equivalent.
L2 - Choke, 25 μh, Mallory type RF-582, or equivalent
R1 - 100K ohms, 1/2 watt
R2, R3, R4, R5, R6, R7, R8, R9, R10, R11 - 50K ohms, 1/2 watt
R12, R13 - 100K ohms, 2 watts adjustable, Ohmite type AB, or equivalent.
R14 - 10K ohms, 1/2 watt
R15 - 50 ohms, 2 watt adjustable, for ballast resistor control.
T1-Vibrator Transformer
V-Vibrator (non-synchronous), Mallory type W659

Fig. 5-3. Self-Contained, Portable Power-Supply Circuit with Voltage Divider for Supplying DC Voltages to RCA Type 6199. Courtesy of Radio Corporation of America.

The scintillating crystal itself must, of course, be protected from external visible light. This is ordinarily accomplished by a thin aluminum covering, which also serves to protect the crystal from the air, as is necessary with sodium iodide. Thickness of this aluminum must be carefully controlled so that it will not exclude the rays or particles being measured.

For some applications, scintillation counters are preferred over Geiger counters. One reason for their differences is that

scintillation counters have better resolution; another is that they can be made with more sensitivity than Geiger counters.

Resolution is a measure of the ability to respond to impulses which originate in rapid succession. It is common for scintillation counters to have resolution times as short as a fraction of a microsecond. Short "dead time", or the time required for recovery after a flash will minimize interference with measurements. This characteristic is very desirable for measuring high intensities.

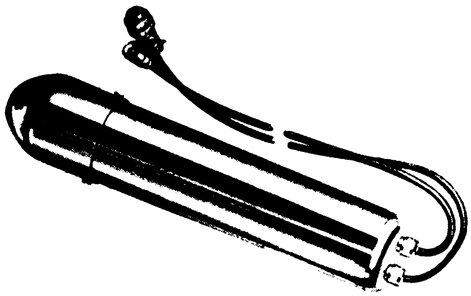


Fig. 5-4. Nuclear-Chicago Model DS-1 Scintillation Detector. Courtesy of Nuclear Instrument & Chemical Corp.

It is possible to make a scintillation counter which has as much as 100 times the sensitivity of a Geiger counter. This makes the scintillation counter valuable for measuring small radiation intensities, and for detecting small variations of intensity. As a result, scintillation counters are valuable for such uses as aerial surveys.

To get a better idea of the basic construction of scintillation counters and to learn what electronic circuitry is required, we will describe a few commercial instruments. This group of instruments is by no means complete or comprehensive, but is representative of current practice. As in the case of Geiger counters, manufacturers are sometimes reluctant to release details on their instruments for competitive reasons.

Nuclear-Chicago DS-1

This instrument, shown in Fig. 5-4, is designed for efficient gamma counting in clinical and laboratory applications. Shielding is arranged to provide excellent ratios of background to source counts when used with a directional shield, or to act as a less directional detector when the shield is removed.

An idea of the basic construction can be obtained from the cross-sectional view of Fig. 5-5. A thallium-activated sodium iodide

crystal 3/4" in diameter and 3/4" long is hermetically sealed in a 1/32" spun aluminum can with a glass window. Light from the crystal is directed to the DuMont Type 6292 photomultiplier tube by means of a lucite light pipe. Optical coupling between this pipe and the

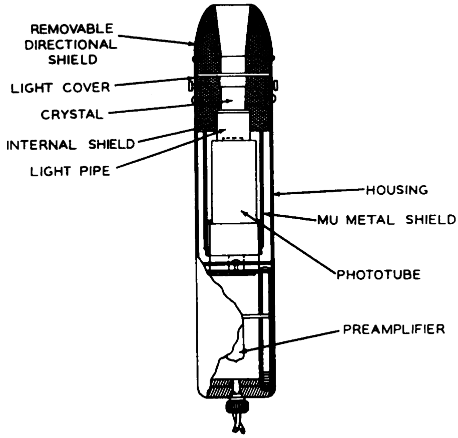


Fig. 5-5. Cross-Sectional View of a Completely Assembled Nuclear-Chicago Model DS-1 Scintillation Detector. Courtesy of Nuclear Instrument & Chemical Corp.

phototube is accomplished with DC-200 silicone oil. Removable lead shields are provided to give the desired directional effects.

As can be seen from the schematic diagram (Fig. 5-6), the photomultiplier circuit is straightforward. Power for the preamplifier is fed to the assembly through one cable, and the high voltage DC is fed through another cable. This second cable also serves as an output cable. About 600 to 1000 volts DC should be available, the exact amount being determined by experiment for a specific crystal and photomultiplier tube.

Voltage for the individual dynodes is obtained from a tapped bleeder resistor consisting of a string of 4.7 megohm resistors. Output pulses are generated across the final anode load resistor (1 megohm) and are coupled to the preamplifier through a 50 mmf capacitor.

Two stages of amplification are provided by the preamplifier, which uses a Type 6U8 triode-pentode tube. The circuit is nonlinear, gain being a function of the amplitude of the input pulses. This arrangement effectively discriminates against noise. Output pulses, which have a minimum amplitude of 1/4 volt, can be fed to any desired instrument, such as a scaler or count-rate meter.

Counting rate of this detector is limited only by the time constant of the preamplifier (20 microseconds), which is short compared to the "dead time" of most Geiger counters. At counting rates as high as 100,000 counts per minute, the coincidence loss will be only about 3%.

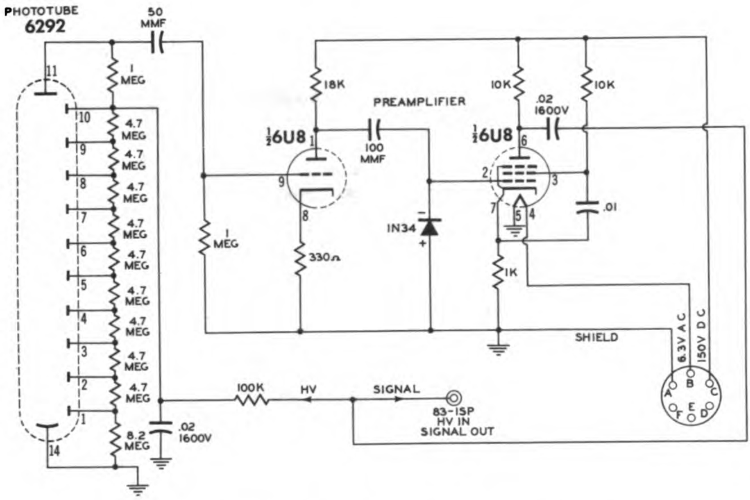


Fig. 5-6. Circuit Diagram of Nuclear-Chicago Model DS-1 Scintillation Detector. Courtesy of Nuclear Instrument & Chemical Corporation.

Precision Model 111 "Scintillator"

A completely self-contained counter, the Precision Model 111 "Scintillator", is shown in Fig. 5-7. It has a sensitivity to gamma rays about 100 times as great as most Geiger counters, making the instrument useful for aerial surveys and surveys from moving vehicles. Ranges of .025, .05, .25, .5, 2.5, and 5 milliroentgens per hour are incorporated, thus providing great versatility.

As can be seen in the photograph, this instrument consists of two separate parts, the probe and the battery case. In the probe, a thallium-activated sodium iodide crystal is optically coupled to an RCA type 6199 photomultiplier tube, which is enclosed in a magnetic shield to prevent defocusing by the earth's magnetic field or other stray fields.

Fig. 5-8 shows the complete circuit of the unit. It is battery operated, requiring two 67 1/2 volt, two 22 1/2 volt, and four 1 1/2 volt batteries. Normal battery life is about 200 hours.

High voltage for the photomultiplier tube is obtained from the low voltage batteries. Neon tube NE-2 (VT 8) is a relaxation oscillator

which pulses the grid of a CK526AX (VT 4) about 100 times per second. Inductor L2 in the plate circuit has a high inductance and produces a high-voltage "kick" as a result of the abrupt current changes through the tube. This "kick" is rectified in tube VT 5, which is either a CK533AX or a 6007 and is specially diode-connected. Good voltage regulation is accomplished by careful choice of circuit constants, and with the Type 5841 voltage regulator tube.

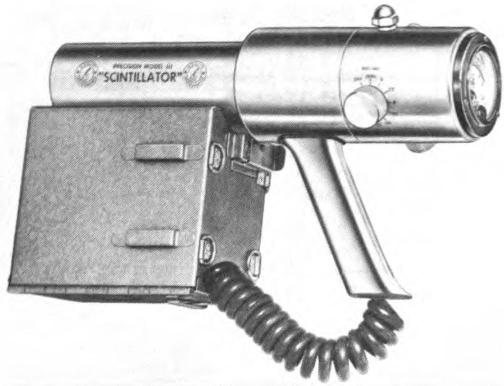


Fig. 5-7. The Model 111 "Scintillator."
Courtesy of Precision Radiation Instruments.

It should be noted that the high-voltage output (about 1000 volts) is negative, and is connected to the cathode of the photomultiplier tube. The final dynode is grounded, and the anode operated at a positive potential with respect to ground. The high voltage bleeder for the various dynodes consists of a string of 22 megohm resistors, except for R11, which is 44 megohms. A one-megohm resistor provides the anode load. Pulses developed across this load are coupled to a one-shot multivibrator circuit consisting of two Type CK533AX or two 6007 tubes. This circuit serves as an equalizer, providing output pulses of equal amplitude and shape, and so produces an indication on the meter that is proportional only to the counting rate.

The steady signal voltage obtained from the plate circuit of VT2 is used to drive the meter through VT3 which acts as a vacuum tube voltmeter. Various ranges are obtained by S1A which switches various values of resistance into the grid circuit of VT3. Two different time constants are provided by S2. The shorter time constant (.01 mfd) permits the meter to follow rapid changes in radiation intensity. With C9 (0.1 mfd) in the circuit, the meter will "settle down" better, but will not follow rapid changes.

A "zero adjust" control (P2) is provided and is used to adjust the meter reading to zero when the range selector switch is in the

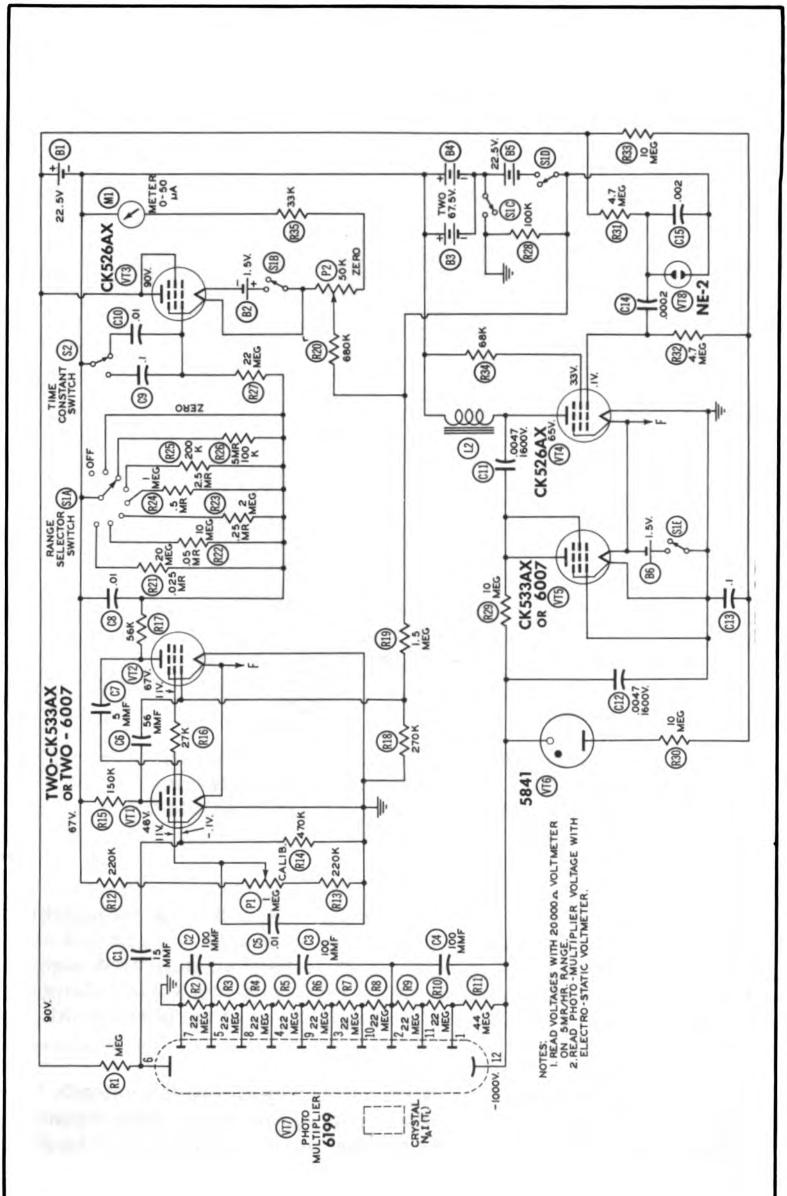


Fig. 5-8. Circuit Diagram of the Precision Model 111 "Scintillator". Courtesy of Precision Radiation Instruments.

zero position. When the instrument is being calibrated, the screen voltage on the univibrator tubes is adjusted by means of a one-megohm potentiometer, P1. This adjustment controls the amplitude of the pulses produced by the univibrator. Calibration must be carried out with a gamma ray source of known intensity.

Fig. 5-9. The Berkeley Model 2250 Scintillation Counter. Courtesy of Berkeley Division Beckman Instruments, Incorporated.

Berkeley Model 2250

This scintillation detector, shown in Fig. 5-9, is designed for counting gamma rays from liquid or solid samples placed in a one-dram glass vial. The crystal, of the thallium-activated sodium iodide, is 1 1/2" in diameter by 1" thick and has a 3/4" diameter hole through its center. It is sealed in a dry atmosphere within an aluminum can with a glass window.

The aluminum can has a re-entrant "well" which extends into the hole in the crystal. Thickness of the can is .025", corresponding to about 170 mg/cm^2. Optical coupling between crystal and the RCA Type 5819 photomultiplier tube is optimized by means of a lucite disc and petroleum jelly.

Fig. 5-10 shows the basic photomultiplier circuit and the cathode-follower output. Proper dynode voltages are supplied by means of a divider with a total resistance of approximately 10.3 megohms. The high voltage (600-1250 volts) is obtained from auxiliary

equipment, and is adjusted experimentally for proper operation. A type 6AU6 tube is triode-connected to provide a low-impedance cathode - follower output. Amplitude of the output is sufficient to drive a commercial scaler or counting rate meter.

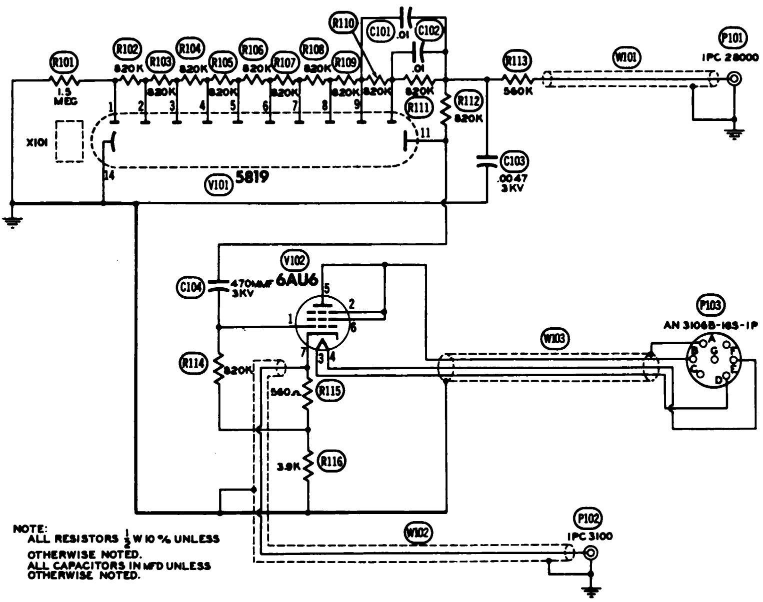


Fig. 5-10. Circuit Diagram of Berkeley Model 2250 Scintillation Counter. Courtesy of Berkeley Division Beckman Instruments, Inc.

Care must be taken when using this counter to make certain that the well does not become contaminated. The standard glass vial used in the well, plus the aluminum crystal housing, provides a total shielding of about 400 mg/cm^2 which screens out all alpha and beta rays, and most of the weaker gamma rays which may be present.

Sherwin SC-10

Designed especially for airborne and ground exploration, the Sherwin Instrument Company Model SC-10 scintillation counter, shown in Fig. 5-11, is an extremely stable and sensitive instrument. It detects weak gamma rays associated with radioactive ores, and has a sensitivity of better than 100 counts per second per microroentgen per hour.

Although the basic instrument operates from a 117 volt, 60 cycle line, suitable converters may be employed to permit operation in any kind of airplane or vehicle. Provision is also made for operation

with a one-milliampere recorder, so a permanent record can be made of the radioactivity in the area under investigation.

The detector head contains an eight-inch "plastifluor" crystal which helps contribute to the high sensitivity. This crystal is optically coupled to the face of a 5-inch photomultiplier tube (DuMont Type 6364) by means of a silicone oil.

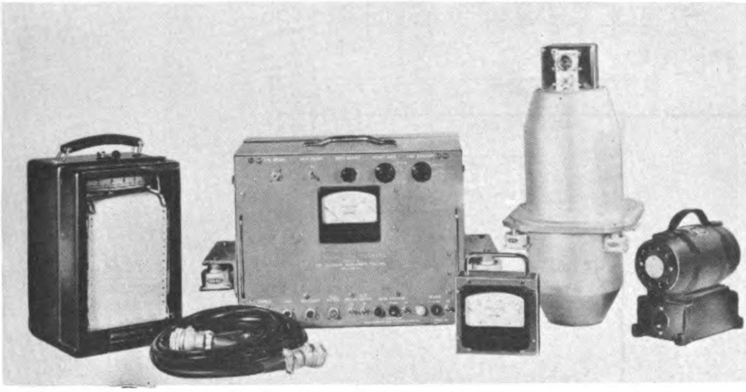


Fig. 5-11. Model SC-10 Scintillation Counter for Airborne and Ground Exploration. Courtesy of Sherwin Instrument Co.

Stability is achieved by careful power supply design, with electronic regulation of both the low-voltage and high-voltage supplies. High voltage is adjustable between 1000 and 1300 volts by means of a screw driver adjusted potentiometer in the high-voltage regulator circuit. The voltage is adjusted for optimum operation with a specific photomultiplier tube and crystal.

A cathode follower output stage is included with the probe assembly. Pulses are fed to a pulse amplifier and then to a special circuit which discriminates against very large and very small pulses. Thus, cosmic rays and random noise are largely eliminated, reducing the background count to a very low value. The discriminator also contains an anticoincidence circuit. Output pulses are fed to the count-rate meter.

The range switch is incorporated in the count-rate circuit, permitting full-scale ranges of 1000, 2000, 20,000, and 40,000 counts per second. Included in this circuit is a time-constant switch which provides time constants of 0.1, 1.0 and 10 seconds. A vacuum-tube voltmeter indicates the voltage in the rate-meter circuit, giving a direct reading of counts per second. An external meter may be plugged in if desired.

R-C Scintiscope

An extremely wide range of radiation intensity measurements is possible with the Scintiscope Model CAX37P made by the R-C Scientific Instrument Co. Eight ranges as follows are incorporated: 0-.05, 0-.5, 0-5, 0-50, and 0-500 mr/hr; 0-5, 0-50, and 0-500 r/hr. The instrument is shown in Fig. 5-12.

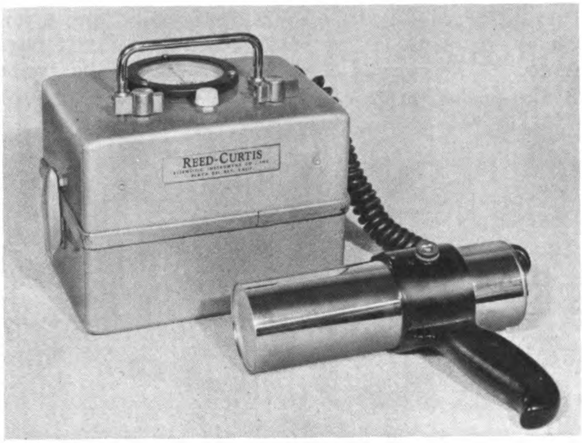


Fig. 5-12. R-C Model CAX37P Scintiscope.
Courtesy of R-C Scientific Instrument Co., Inc.

An RCA Type 5819 photomultiplier tube is employed in the scintillation head. High voltage is obtained from three 300-volt batteries connected in series. The anode of the 5819 is approximately at ground potential, and is direct - coupled to a DC amplifier consisting of two 1LB4 tubes. Sensitivity is altered for the various ranges by changing the voltage applied to the various dynodes of the 5819.

The amplifier consists of a form of balanced bridge circuit with a meter used to indicate the degree of unbalance. When radiation is being detected, the voltage on one 1LB4 grid varies, while that on the other remains fixed. This unbalances the bridge and causes the meter to read. Various resistors and capacitors are included in the meter circuit to adjust meter sensitivity and to provide suitable damping.

A 2000-ohm potentiometer connected in the filament-return circuit provides a zero adjustment. It serves to balance the bridge when no radiation is being detected, and can adjust for minor differences in the 1LB4 characteristics. The tap on this potentiometer is returned to a point 45 volts negative with respect to ground, which is also the potential of the last dynode of the 5819. Since the anode of the 5819 is at ground potential, the plate is operated at 45 volts positive with respect to the last dynode, except for the three most sensitive ranges.

Plate current for the 5819 must pass through a 22-megohm resistor which serves both as a plate load for the 5819 and the grid resistor for the 1LB4 forming the variable arm of the bridge circuit.

On the three lowest ranges, the ground potential of the circuit is varied by a voltage divider arrangement in such a manner as to increase the anode potential on the 5819, increasing the sensitivity.

Because of its wide range, this instrument is very versatile. The scintillating crystal and photomultiplier tube are mounted in a probe which is connected to the battery and meter carrying case by a 7-foot cable. Crystals are interchangeable, so the probe can be adapted for the detection of alpha, beta, or gamma rays, or thermal neutrons.

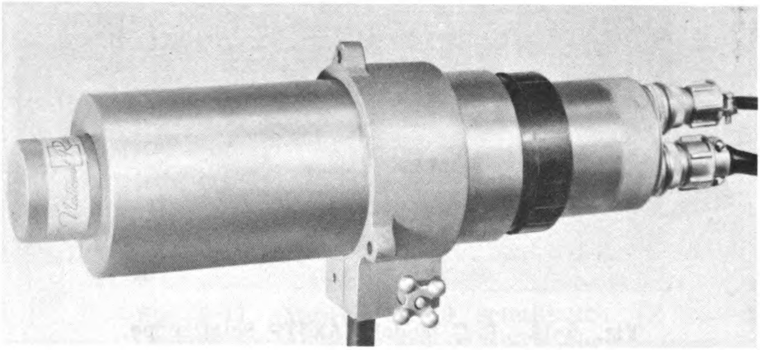


Fig. 5-13. National Radiac General Purpose Scintillation Head. Courtesy of National Radiac, Inc.

National Radiac Scintillation Head

Shown in Fig. 5-13 is a general-purpose scintillation head which may be used with twelve different types of crystal detectors for measuring alpha, beta, gamma, or x-rays, or neutrons. A lead shield may be added to provide for directional counting, as in medical applications, or for the reduction of background.

The head illustrated in Fig. 5-13 is unshielded and fitted with a sealed sodium iodide crystal which protrudes so that it can be inserted in the radiation beam being measured. This arrangement is used when gamma rays are of interest.

For alpha measurements, a crystal of the type shown in Fig. 5-14A is useful. Details of construction are apparent from the cross-sectional drawing of Fig. 5-14B. A tightly packed layer of alpha sensitive phosphor crystals (1) is mounted on a lucite disc (2) and covered by a hole-free aluminum foil, 0.7 mg/cm^2 thick (3). This assembly is mounted in a sealed aluminum container (4) which has an ultraviolet transmitting glass window (5). The end of the container

is perforated (6) providing access to alpha particles and protection to the thin end-window.

Beta measurements may be made by means of the beta ray crystal detector shown in Fig. 5-15A. The cross-sectional drawing, Fig. 5-15B, shows the construction. A slice of a single crystal of

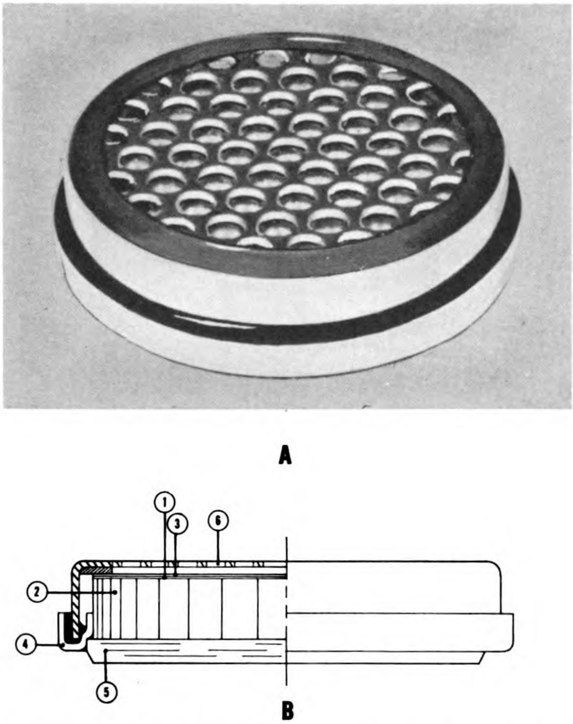


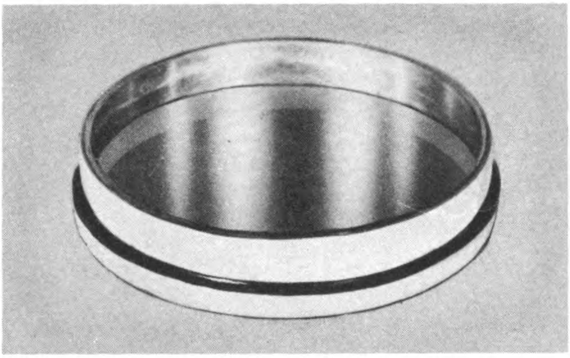
Fig. 5-14. (A) Alpha Scintillation Detector. (B) Cross-Sectional Drawing of Alpha Scintillation Detector. Courtesy of National Radiac, Inc.

stilbene (a scintillating phosphor) 1/2 mm thick (1) is mounted on an ultraviolet transmitting glass window (2) and covered by an aluminum foil (3) which has a thickness of 3.5 mg/cm^2.

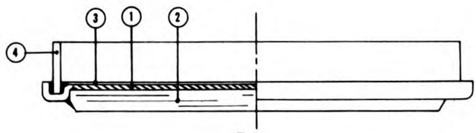
When changing crystals, a silicone oil or grease is used to form a light-transmitting seal between the glass of the crystal assembly and the face of the photomultiplier tube. This arrangement permits maximum light transfer from the scintillating crystal to the active portion of the photomultiplier.

Two different models of the head are available. Model SA-2 has a built-in, two-stage 12AX7 amplifier with a gain of 10. A

cathode-follower model, SC-2, is also made. It is used where the highest resolution or most rapid rise time is desired, and is preferred by research laboratories. For routine laboratory or medical counting, the two-stage amplifier is more desirable. It provides scintillation pulses in excess of 1 volt output at the highest counting rate likely to be encountered, and will operate conventional scalers without the need for additional amplification. Both models have low output impedance and can be used with cables up to 50 feet long.



A



B

Fig. 5-15. (A) Beta Scintillation Detector. (B) Cross-Sectional Drawing of Beta Scintillation Detector. Courtesy of National Radiac, Inc.

This head will operate satisfactorily with the DuMont 6292, the RCA 5819, or the RCA 6342 photomultiplier tubes. The 6292 provides the highest resolution and requires an applied potential of 1400 to 1700 volts. With the 5819 or 6342, 1000 to 1300 volts is necessary.

Miscellaneous

We have only touched on a few of the many scintillation counters on the market. Some specialized components and materials are worthy of mention, in addition to those covered previously in this chapter and in Chapter 3.

Wakefield Industries, Inc., in cooperation with another company, has developed an extremely thin mylar film which is coated on both sides with aluminum to provide a light-tight covering for scintillation

phosphors. Nominal thickness is 0.9 mg/cm^2, which will admit even fairly weak alpha rays.

Another product manufactured by this company, as well as others, is a liquid scintillation material. The Wakefield product consists of terphenyl dissolved in a substance called metaxylene. Light yield is 0.46 that of anthracene.

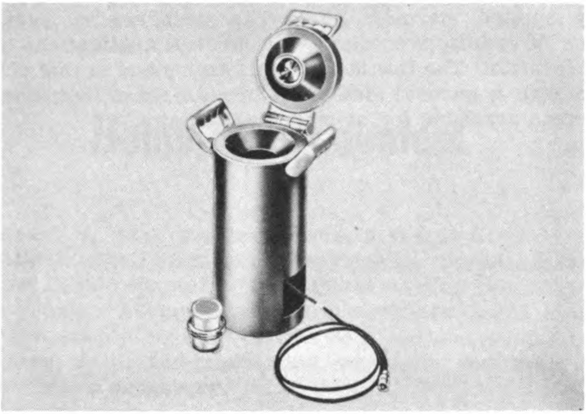


Fig. 5-16. Model SC-12 Liquid Sample Counter. Courtesy of Nuclear Research and Development, Inc.

When it is desired to measure the radioactivity of a liquid, a liquid sample counter such as the Nuclear Research and Development Company Model SC-12 may be used. This counter, shown in Fig. 5-16, is one of the most sensitive instruments available for the measurement of gamma emitting liquids. A sensitivity of 1000 counts per minute for one millimicrocurie of radioactive iodine (I^{131}) is obtainable. It is estimated that this sample counter will detect 50% of all gamma rays given off by a small sample of I^{131} .

Future Developments

As with Geiger counters, a considerable amount of development work is underway on scintillation counters, and improvements in performance will undoubtedly be evident as time goes on.

Perhaps the most significant development will be the employment of transistors to generate the high voltage for the photomultiplier tube, and to provide amplification of the output pulses. Such applications will reduce battery requirements, which will be particularly advantageous on portable survey instruments. One or two commerical instruments now on the market make use of transistors in their circuitry.

Photomultiplier tubes have reached a high state of development, but may perhaps be improved even further to provide greater gain

and less background noise. With large-scale use, it is even possible that the price may be reduced somewhat.

Scintillation counters will find more and more applications in the field of radioactive isotopes for tracer work of all kinds, as well as in airborne surveying. Their extreme sensitivity, coupled with ruggedness and reliability, make them useful in field work where small variations in intensity are significant. Directive shielding, properly applied, permits pin-point accuracy in locating small quantities of radioactive material in medical applications and tracer work of all kinds. The few instruments described in this chapter will serve to give a general idea of the broad field of instruments which have become available for scintillation counting.

CHAPTER 6

Home-Built Counters

Contrary to most popular beliefs, a simple Geiger counter is neither difficult to build nor excessively costly. Several designs will be discussed in this chapter, the simplest costing less than $20.00 at current prices. All components are readily available from most of the larger supply houses. Tools required consist primarily of soldering iron, drill, and pliers, and very little knowledge of electronic circuitry is necessary.

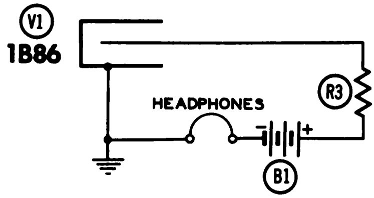
As the designs become more complicated, more knowledge and skill are desirable. This is especially true of scintillation counters, although even here the careful beginner can construct usable equipment. The designs to be presented in this chapter are no more complicated than a small radio receiver, and certainly no more difficult to construct.

It is recommended that the serious constructor review Chapters 4 and 5 very carefully before embarking on a construction project. A fairly intimate knowledge of the design of commercial instruments can be of immense help when trying to decide which type of counter to build, and which circuit to use. Also, the ultimate application of the instrument should be considered carefully. If the primary purpose is for uranium and thorium prospecting, read Chapter 10 carefully to help in reaching a decision. For general survey work, area monitoring, civil defense, etc., Chapter 9 should be of help. In radioactive tracer work, other material should be studied to supplement the information appearing in this book. In general, it should be emphasized that the scintillation counter can be far more sensitive, and is more expensive, than the average Geiger counter.

This chapter is divided into three general parts. First, there is a discussion of several Geiger counter designs. Next is a presentation of a practical scintillation counter. The third part discusses some high voltage power supplies, which could be used for either a Geiger counter or for a scintillation counter.

Whenever you work with circuits of this type, there are several basic construction points to keep in mind. For instance, always keep

hook-up wire leads as short as practical; avoid unnecessarily long leads which will tangle in the equipment. This makes circuit tracing and trouble-shooting difficult, and often increases the capacity between leads enough to interfere with proper circuit operation. Make each connection mechanically secure before you solder it, so the soldered joint will not break due to strain. Always use rosin-core solder (rather than acid-core) to insure long lasting connections without corrosion. When you solder, heat the material which is to be soldered before you apply the solder, and flow just enough solder into the connection to secure it tightly. Avoid cold-solder joints and large masses of metal; they not only look bad, but they can actually interfere with circuit operation. If you are not familar with construction of electronic circuits, examine some commercial radio equipment for samples of workmanship before you begin your work.



PARTS LIST

R3 — 1 meg, 1/2 watt
B1 — 300-volt Battery (Eveready or Burgess)
V1 — Victoreen 1B86 Geiger Tube
Headphones — Sensitive high Impedance headphones.

Fig. 6-1. The Simplest Geiger Counter.

Geiger Counters

We learned in Chapter 4 that a Geiger counter can be extremely simple, or can be more complex, depending on the results desired. In some cases, clicks in a pair of headphones provide sufficient indication of radiation intensity; at other times the flashing of a neon light makes a desirable indicator; and in perhaps the majority of applications, a meter reading provides the most satisfactory indication.

The simplest Geiger counter which you can build is diagrammed in Fig. 6-1. As can be seen, it is a straight series circuit with the battery, Geiger tube, protective resistor, and headphones connected in series. The tube and battery must match — that is, a 300-volt battery must be used with a 300-volt tube, and a 900-volt battery with a 900-volt tube. Fortunately, very small, light-weight 300-volt batteries have been developed, so the size of the power supply can be minimized.

Certain precautions are necessary in building even this simple unit. In the first place, the 300 volts from the battery can give a

wicked bite, so watch out! Secondly, magnetic-type headphones must be used rather than the crystal type, since a DC path must be available for the battery current. Actual battery drain in a circuit of this type is very small, and battery life approaches shelf life, even with extended use.

Geiger tubes are available for both 300 volt and 900 volt operation. Mechanical construction will depend on the type of tube used — some have wire leads only, and some fit into a special socket. Since most of the tubes are glass, they should be placed in a metal enclosure for protection. This enclosure should be perforated at appropriate points below the tube to avoid shielding the rays which are of interest.

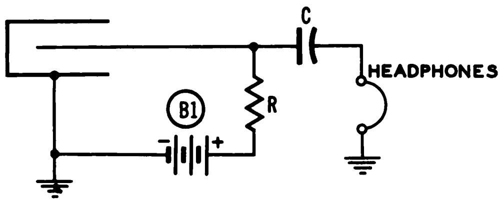


Fig. 6-2. Circuit for Eliminating DC from Headphones. C is a 0.01 Mfd Ceramic Capacitor, R Can Be from 1 to 5 Megohms.

One of the penalties which must be paid for an extremely simple circuit of this nature is lack of headphone volume. Even with sensitive phones with an impedance of 2,000 ohms or more, volume will leave a lot to be desired, particularly in noisy locations. Crystal headphones can be utilized for increased sensitivity by taking advantage of the circuit of Fig. 6-2. Here the DC path is provided by a load resistor, and the impulses from the Geiger tube are coupled to the headphones by means of a capacitor.

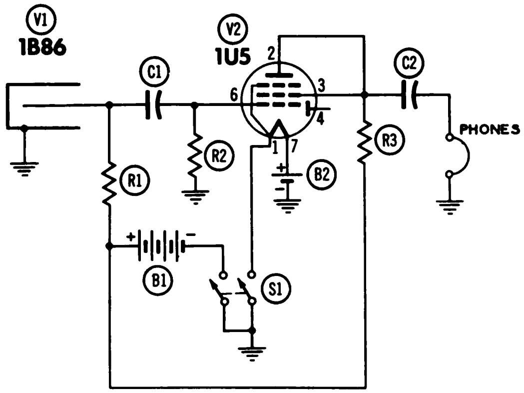
A simple, one-stage amplifier may be added to the circuit shown above to give greatly increased volume. Such a circuit was described by the author in the January, 1955 issue of Popular Electronics.[1] The complete circuit and parts list is shown in Fig. 6-3, and views of the complete unit are presented in Figs. 6-4 and 6-5.

The amplifier consists of a triode-connected 1U5 tube, whose filament (50 ma at 1.5 volts) is supplied by an ordinary penlite cell. This particular unit uses a 300-volt Geiger tube and a 300 volt battery. To overcome the necessity of providing an extra B battery for the 1U5 plate circuit, use the 300-volt battery and a large plate load resistance (1 megohm). If you use a 900-volt Geiger tube for this circuit, use two additional 300-volt batteries in series between the +

1 H. S. Renne, Fun with a Geiger Counter, Popular Electronics, January, 1955, p. 78.

terminal of B1 and the bottom of R1, as shown in Fig. 6-3. Connect the 1U5 plate circuit across only one battery, so its total voltage source is only 300 volts.

Be sure the voltage rating of the capacitors is high enough to match the circuit voltage, either 300 volts or 900 volts. Ceramic capacitors take up less space and usually have a higher voltage rating than tubular types, but either kind may be used. Resistance values are not critical, and ± 20% commercial tolerances are entirely satisfactory.



PARTS LIST

R1, R2 — 4.7 megohm, 1/2 w. res.
R3 — 1 megohm, 1/2 w. res.
C1, C2 — 0.01 mfd ceramic capacitor
B1 — 300 v. Battery (Eveready or Burgess)
B2 — 1 1/2 v. penlite cell
S1 — DPST toggle switch
V1 — Victoreen 1B86 Geiger tube
V2 — 1U5 tube
Headphones — Sensitive, high-impedance headphones

Other parts you will need: one 3" x 4" x 5" aluminum box; one kitchen cabinet handle; one Fahnestock or similar clip; one clip for battery; two phone tip jacks; one 7-pin miniature tube socket; one 5-lug terminal strip; screws, nuts, wire, and solder.

Fig. 6-3. Circuit of a Geiger Counter with an Amplifier Added.

Either crystal or high-impedance phones will work in the output circuit. Use blocking capacitor C2 for either type of phones to prevent any possibility of shock from them.

The original model of this particular counter was built in a commercial 3" x 4" x 5" aluminum cabinet with an ordinary kitchen cabinet door pull for a handle. A series of holes was drilled underneath the Geiger tube to permit easy entry of the rays being measured. The Geiger tube may be fastened in place by any suitable

clamp. A clamp bent from a Fahnestock clip was found to be highly satisfactory. It is a good idea to glue two or three small pieces of felt or sponge rubber between the tube and the clamp to provide protection from shock and excessive clamping pressure.

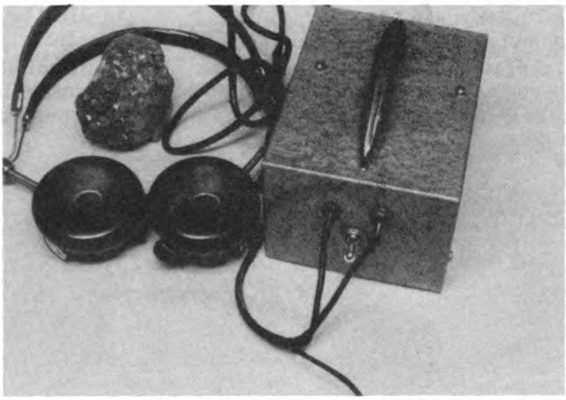


Fig. 6-4. Over-All View of Counter with Amplifier.

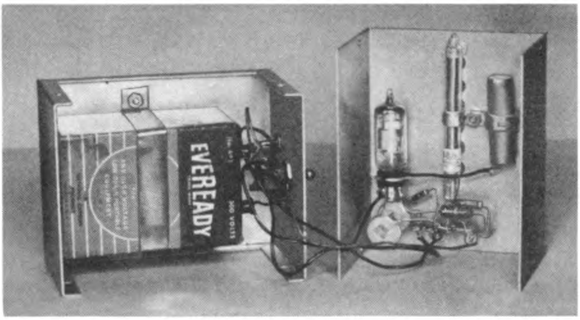


Fig. 6-5. Interior View Showing Construction Details of Counter of Fig. 6-4.

Use solid hook-up wire for the tube socket connections. It will support the socket and tube and eliminate the necessity of mounting the socket rigidly to the case. This method of assembly provides a sort of shock mount, and helps protect the tube in case of a severe shock. Use a terminal strip to simplify the wiring; locate it near the lower end of the Geiger tube, as shown in Fig. 6-5.

No adjustments are necessary after the unit is built. If all wiring is correct, and all components, including the 1U5 tube and batteries, are good, you will hear clicks in the headphones as soon as you turn on the switch. These clicks are the background count,

and will be heard at the rate of about 40 or 50 a minute. Any appreciable increase in this rate probably indicates that there is some radioactive material in the vicinity.

This instrument is particularly useful for prospecting, since it is light, rugged, and reliable. However, it can also be used for checking objects for the presence of radioactive material, such as clothing, laboratory benches, and the like. It is difficult to determine exact radiation levels with this unit, but comparative measurements may be made by counting the clicks in a certain period of time, say one minute.

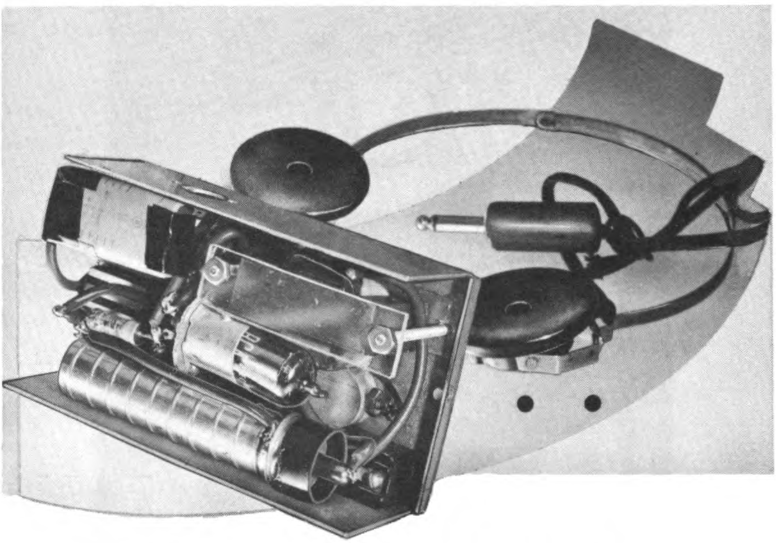


Fig. 6-6. Simple Geiger Counter Using the Circuit of Fig. 6-7. Courtesy of Radio & Television News.

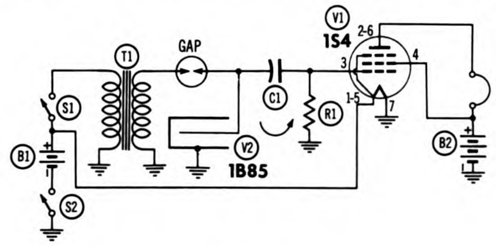
Another simple counter was described in the July, 1954, issue of Radio & Television News.[2] The unit is illustrated in Fig. 6-6 and its schematic diagram is shown in Fig. 6-7. It uses a high ratio step-up transformer and a spark gap rectifier to obtain about 900 volts for the 1B85 Geiger tube.

Transformer T1 has to be specially connected to obtain the high step-up ratio. Connect the 8-ohm winding as the primary in Fig. 6-7, and the 8000-ohm winding as the secondary. Use a normally open Microswitch for S1. When you press down on the Microswitch, you close a circuit so the 1 1/2 volt battery B1, sends a current through the 8-ohm winding. Due to the inductance in the winding, current builds up slowly to its maximum. When you release the

---

2 Dr. H. R. Fechter and Dr. R. M. Boyd, A Simple Geiger Counter, Radio & Television News, July, 1954, p. 35.

switch, current is stopped suddenly. Voltage is induced in the secondary when the switch is closed and when it is opened, but a larger voltage is induced when the switch is opened. Set the finely filed and stoned points of the two spark-gap set screws close enough so they will ionize with the larger voltage applied, but will not with the smaller voltage. The specially constructed spark gap, shown in Fig. 6-8, acts as a rectifier and allows a current to flow and charge up capacitor C1. When an ionizing event occurs in the 1B85 tube, the capacitor dis-



PARTS LIST

R1 — 10 meg, 1/4 watt resistor
C1 — .05 mfd, 600 v capacitor
S1 — Microswitch (or equiv.)
S2 — SPST toggle sw.
T1 — Universal type output trans. 5000 to 8000 ohm pri. to 4 to 8 ohm sec.
B1 — 1.5 v flashlight cell
B2 — 22.5 v hearing aid battery
Gap — See text and Fig. 6-8.
One headphone
V1 — 1S4 tube
V2 — 1B85 (Victoreen)

Fig. 6-7. Schematic Diagram and Parts List for Simple Geiger Counter.

charges slightly. This produces a voltage pulse which is applied to the grid of the 1S4 amplifier tube. The amplified pulse will then cause a click in the headphones in the 1S4 plate circuit.

The voltage which is applied to the Geiger tube needs to be positive at the center wire and negative at ground. If the polarity of the voltage is wrong when you connect the circuit as described above, reverse the connections for either the primary or the secondary winding of transformer T1.

To start circuit operation, press and release switch S1 several times, until sufficient charge has accumulated on capacitor C1 to operate the Geiger tube. Stop when you hear normal clicks in the headphones, or you will increase the voltage enough to damage the Geiger tube. When the charge on C1 has been reduced so you can no longer hear the clicks, renew it by pressing switch S1 several times. When it has been charged, the counter should operate for a period of from 5 to 30 minutes. The total time will depend on the quality of your components and, to a certain extent, on the relative humidity. High humidity will allow a more rapid discharge of the capacitor by reducing the external leakage resistance.

The 1. 5-volt battery B1, furnishes power for the high voltage circuit, and also for the filament of the 1S4 amplifier. Battery B2 is a 22. 5-volt hearing aid type, and furnishes plate and screen voltage for the 1S4. Because current drain through them is very small, both batteries have a fairly long use life.

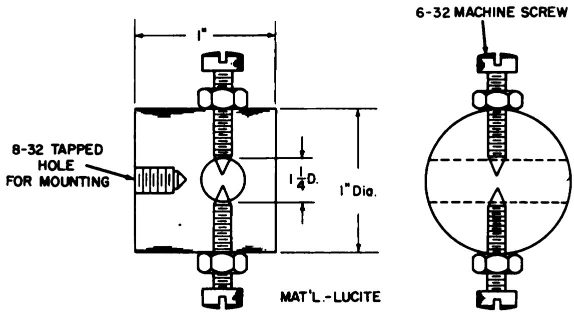


Fig. 6-8. Details of Spark Gap Construction.

Be careful when you build and operate this device. Use high quality components throughout the circuit. Capacitor C1 must have a good insulation resistance to prevent it from losing its charge too rapidly. Be sure to discharge the capacitor before you reach into the unit after it has been used; the voltage which is stored up in the capacitor is dangerous for you to contact.

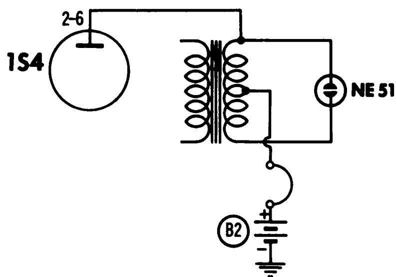


Fig. 6-9. Scheme for Adding a Neon Light Flasher to Circuit of Fig. 6-7.

Clicks in a pair of headphones serve as the normal indication of radiation intensity. If desired, you can add a neon flasher to provide a visual indication too. A suitable circuit for this was described in the January, 1955, Radio & Television News.[3] It is shown in Fig. 6-9.

3 Marcus E. West, Geiger Counter Flasher, Radio & Television News, January, 1955, p. 84.

Use the primary winding of a push-pull audio output transformer to set up the neon lamp circuit. Change battery B2 to 45 volts to increase the amplification of the 1S4 tube. Clip the transformer leads off short, and connect the center tap to B+ through the high impedance headphones. Connect one side of the transformer

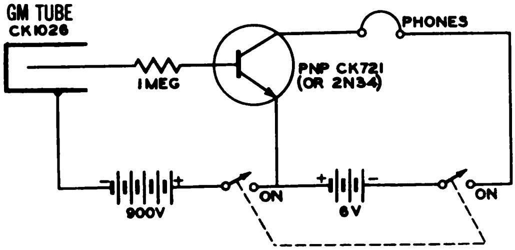


Fig. 6-10. Circuit for Geiger Counter with Transistor Amplifier.

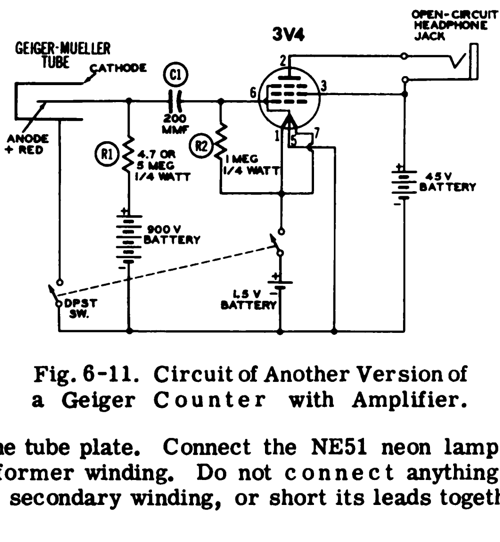


Fig. 6-11. Circuit of Another Version of a Geiger Counter with Amplifier.

winding to the tube plate. Connect the NE51 neon lamp across the entire transformer winding. Do not connect anything across the transformer secondary winding, or short its leads together.

Some simplification in the circuitry and battery requirements of a Geiger counter can be made by using a transistor amplifier instead of a vacuum tube. Such a circuit appeared in the July, 1954 issue of Radio-Electronics,[4] and is reproduced as Fig. 6-10. An extremely simple grounded-emitter amplifier circuit provides a gain of about 7, depending on the transistor characteristics.

---

4 N. O. Sokal and I. L. Resnick, A Transistorized Geiger Counter, Radio-Electronics, July, 1954,

Although this specific circuit employs a 900-volt battery and 900-volt Geiger tube, operation would be satisfactory with a 300-volt tube and battery.

Remember, 900 volts is dangerous! Be careful when you are working around such a high voltage. Do not touch any part of the circuit where such a high voltage exists.

Another variation of the audio amplifier type of counter was described in the July, 1950 issue of Popular Mechanics.[5] The circuit is reproduced in Fig. 6-11.

In this unit, a 900-volt Geiger tube (Raytheon CK-1021 or equivalent) is powered by three 300-volt batteries connected in series. Any other power supply which will provide 900 volts could be used. When the Geiger tube ionizes, current through it creates a voltage pulse across the 4.7 (or 5) megohm resistor R1. The pulse is coupled to the grid of the 3V4 amplifier tube with the 200 mmf capacitor C1. Amplified pulses produce clicks in high-impedance headphones plugged into the headphone jack. Crystal phones will not work in this circuit because they will not allow the DC plate current to flow through the amplifier tube. A 1.5-volt flashlight battery is used for filament power for the 3V4.

A somewhat more complicated Geiger counter circuit which includes a meter for indicating radiation intensity is shown in Fig. 6-12. This unit was described in the February, 1952 issue of Radio & Television News.[6] Power is obtained from two series-connected 67.5-volt batteries and three parallel-connected standard 1.5-volt flashlight cells.

Reference to the circuit diagram of Fig. 6-12 will show that voltage is applied to only one-half of the filament in V1 and V4. The battery drain is thereby cut in half and no decrease in performance is detectable in this circuit application.

Tube V1 and its associated components form a relaxation oscillator. The "B" battery voltage is applied to capacitor C1 through resistor R1. Neon lamp NE1 (which is a type NE-2) will ionize when the capacitor has stored up enough voltage to fire it. Then the capacitor will discharge through the neon lamp until the voltage is low enough for the lamp to be extinguished. This cycle repeats as long as the voltage is applied. In this circuit, the wave shape is a saw tooth and the frequency is about 800 cycles per second.

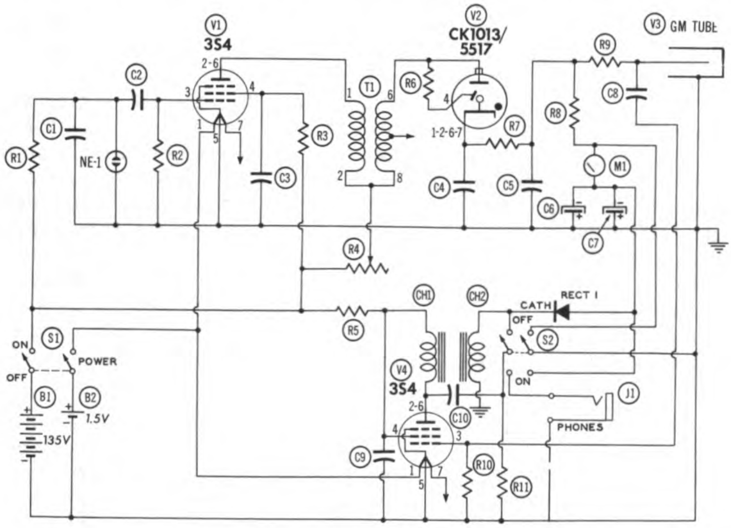
The 3S4 tube, V1, amplifies the saw tooth voltage. The plate load is the primary winding of transformer T1, so the output voltage

---

5 Uranium Survey Meter with Audio Amplifier, Popular Mechanics, July, 1950, p. 160.

6 Loren C. Watkins, Jr., A Professional Type Geiger Counter, Radio & Television News, February, 1952, p. 35.

is transformer coupled to the input of the cold cathode rectifier circuit. A very high voltage results from the connections as they are shown in Fig. 6-12. After it is rectified by tube V2, the DC voltage is applied to a filter consisting of resistor R7 and capacitors C4 and C5. The filter removes most of the ripple from the DC voltage.



PARTS LIST

R1 — 6.8 meg, 1/2 watt resistor
R2 — 22 meg, 1/2 watt resistor
R3 — 47,000 ohm, 1/2 watt resistor
R4 — 50,000 ohm potentiometer
R5 — 100,000 ohm, 1/2 watt resistor
R6, R9, R10 — 10 meg, 1/2 watt resistor
R7 — 470,000 ohm, 1/2 watt resistor
R8 — 30 meg, 1/2 watt resistor (Two 15 meg in series)
R11 — 1 meg, 1/2 watt resistor
C1 — 400 mmf mica capacitor
C2 — .001 mfd mica capacitor
C3 — .002 mfd mica capacitor
C4 — .002 mfd, 2000 v capacitor. ("Glass-mike" Type LSG202)
C5 — .05 mfd, 2000 v capacitor. ("Glass-mike" Type ASG17)
C6, C7 — 500 mfd, 12 v electrolytic
C8 — 500 mmf, 2000 v capacitor. ("Glass-mike" Type LSG501)
C9 — .01 mfd, 400 v capacitor
C10 — .005 mfd mica capacitor
S1 — DPST toggle sw.
S2 — DPST toggle sw.
T1 — Interstage trans. (UTC "Ouncer" Type 0-7)
CH1, CH2 — Reactor (UTC "Ouncer" Type 0-13)
M1 — 0-100 microammeter
J1 — Midget open circuit phone jack

Rect. 1 — 1N34 crystal diode
NE1 — NE-2 neon lamp
B1 — Two 67.5 v "B" batteries (Eveready No. 467 or equiv.)
B2 — Three 1.5 v standard flashlight cells, 1 5/16" dia.
V1, V4 — 3S4 tube
V2 — CK1013/5517 tube
V3 — Victoreen Type 1B85 or equiv.

Fig. 6-12. Schematic of a Unit with a Meter and an Oscillator-Type of High Voltage Supply.

The variable resistor R4 controls the high voltage output of the power supply for a range of about 500 to 1250 volts, with new batteries in use. This resistance acts to vary the efficiency of the V2 plate circuit. As the batteries age, the control is adjusted to insert less resistance in the circuit, thereby increasing the efficiency, and permitting operation at 900 volts output until the batteries are expended. This point will have been reached when the battery voltage

(under load) drops from its original 135 volt value to about 95 volts. The output voltage changes slightly with aging of the filament batteries, until they have dropped from the original 1.5 volts to about 0.8 volt. The output voltage regulation, as a function of the external load, is quite adequate for a Geiger tube having a normal flat-plateau characteristic. If the tube does not have a flat characteristic, and at unusually high counting rates, the voltage is readjusted to the proper operating potential by a slight variation of output control R4.

The amplifier stage V4, has a switch in its output circuit so that either headphones or the meter, M1, may be used to monitor the count. The signal pulses from the Geiger tube are coupled into the signal grid of V4 via C8. The amplified pulses appear across the plate circuit inductance CH1, where they are capacitively coupled to the indicating circuit. The "phones" switch S2, is connected so that in its "on" position the headphone jack J1, is connected across the output of V4, allowing individual pulses to be counted. Stray circuit capacity from the neon oscillator and associated circuits provides a weak audio tone in the V4 amplifier output, indicating that the instrument is operating, and that the batteries are not expended.

In the same switch position, the negative terminal of M1 is returned directly to ground. The meter, therefore, is effectively connected in series from the bottom end of the high-voltage bleeder resistor R8 to ground, and provides an accurate indication of the power supply output voltage. This assumes that the bleeder resistance value is accurately known. For example, if the bleeder resistance is 30 megohms, an indicated current of 30 microamperes requires the presence of 900 volts across the bleeder, according to Ohm's law. Other current values are interpreted accordingly, as the voltage output control is varied.

When S2 is thrown to its "off" position, the headphones are disconnected and the amplifier output is connected into the 1N34 diode circuit. The rectified pulses are fed to the integrating capacitors C6 and C7, which allow the meter to indicate the average counting rate. The other side of S2 connects the positive terminal of the meter and the bottom of the bleeder resistance directly to ground, thereby removing the meter from the bleeder circuit.

It is unnecessary to provide a scale on the meter other than its original calibration, because the meter is used mainly in a relative sense when it is indicating a counting rate. The background count will show a small reading which you will use as the reference. When the meter reading increases, it shows the presence of radiation activity.

Do not adjust the voltage control R4, to a position where the voltage is great enough to cause the Geiger tube to "spill" or discharge continuously. This would reduce the life of the Geiger tube. Leave the Geiger tube disconnected until you have 900 volts available to apply to it.

If you cannot get the high voltage up to 900 volts, as indicated by a meter reading of 30 microamperes when the "phones" switch is set at "on", resistor R16 may have too small a value. Increase its resistance in 100,000-ohm steps to try to get the 900-volt output. If necessary, remove the resistor completely and leave pin 4 of tube V2 floating.

Fig. 6-13. Over-All View of Unit Whose Circuit is Shown in Fig. 6-12. Courtesy of Radio & Television News.

Fig. 6-13 shows the completed counter; interior views showing some of the construction details are shown in Fig. 6-14A and 6-14B. Follow this parts layout as closely as possible to prevent too much feedthrough of the oscillator tone into the amplifier. Excessively long leads, resulting in a large stray capacity, can cause such trouble.

A probe housing inside the case is partially visible in Fig. 6-14A. It is located directly in back of the batteries. Make it from a 5-inch length of lucite tubing, with an inside diameter slightly greater than the outside diameter of the brass probe shell which houses the Geiger tube. Use two U-shaped brackets to hold the lucite tube in the case. Tighten these brackets so there is a slight pressure

against the outside of the shell which will hold it in place. Cut a hole through the end of the metal case through which you can insert the probe in the lucite holder.

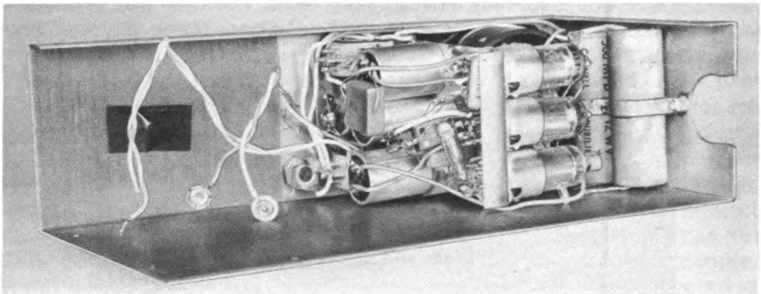


Fig. 6-14A. Completed Assembly View Showing Subchassis and Battery Mounting Details. Courtesy of Radio & Television News.

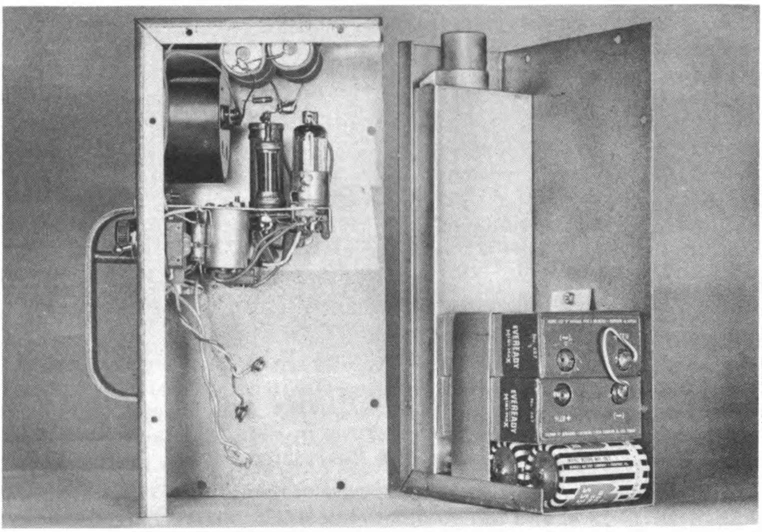
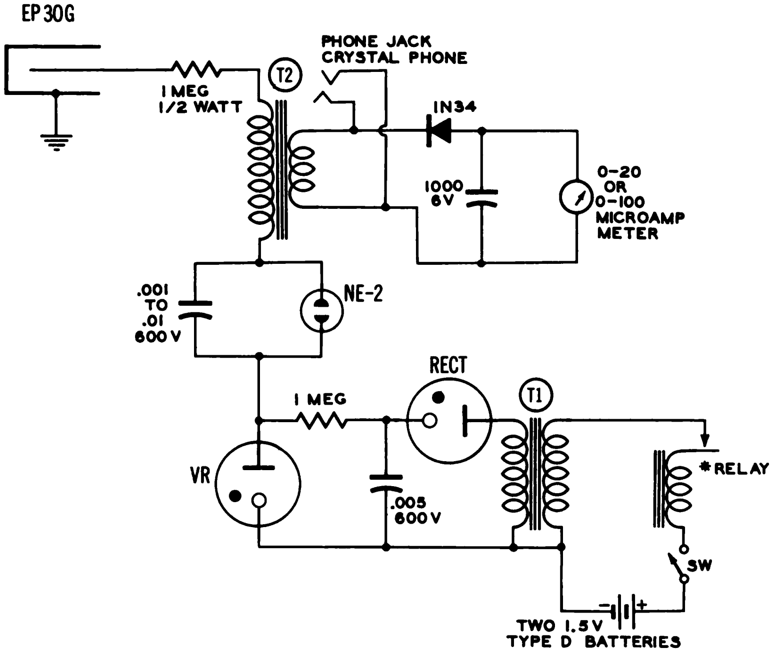


Fig. 6-14B. Rear View of Instrument Showing Parts Layout. Courtesy of Radio & Television News.

Use a 10-inch length of thin walled brass tubing with a 1-inch inside diameter for the probe. Drill seven 1/2 inch diameter holes through one side of the brass tube in a straight line. Two of these holes can be seen in the portion of the probe which shows in Fig. 6-13. Float the Geiger tube inside the brass shell by wrapping several layers of "Elastoplast", an elastic adhesive bandage material, around the tube at each end to provide a snug sliding fit. Use rubber

stoppers to seal the ends of the probe. Use a solid stopper at the free end, and a one-hole stopper at the cable end of the probe. Press the stoppers in for a tight fit and then strip them off even with the ends of the probe. Make the cable about four feet long of flexible and well insulated wire. Insert it through the hole in the stopper and secure it to the stopper to provide strain relief to the Geiger tube. Push the unused cable down inside the case when the probe is not in use.



*Suggested Relay Types (All SPST NC Contacts):

Advance Electric & Relay Co.
Type 5002 15-volt ac coil
104 AM-2A 15-volt ac coil

Allied Control Co.
Type BC coil #28 (8.8 ohms)
F coil #32 (7.5 ohms)
SK coil #28A (7.7 ohms)

Sigma Instrument Co.
Type 5F (16-ohm coil)

T1, T2 — Thordarson Type 20A00
VR — Electronic Products Co. Type EP 30 RS
Rect — Raytheon CK-1013

Fig. 6-15. A simple Geiger Tube Circuit with Neon Tube Flasher, Meter Indicator and Headphone.

When the unit is not in use, the search probe fits inside the holder in the case. For normal use, pull the probe out about three-quarters of its length. When desired, for exploring otherwise inaccessible areas, remove the probe completely from the case.

Several Geiger counter circuits are suggested in Bulletin No. NYO-103 written by H. D. LeVine and published by the New York

Operations Office of the Atomic Energy Commission.* All use an interrupter-type power supply with the high inductive kick in a step-up transformer to provide the high voltage. One of the circuits is reproduced in Fig. 6-15.

The high voltage pulses are rectified by a Raytheon type CK-1013 rectifier tube and regulated by VR. A step-down audio transformer with the high impedance winding in series with the high voltage to the Geiger tube provides a high-current low-voltage pulse for the meter and headphone circuit. A turns ratio of about 20 to 1 is satisfactory for this transformer. A germanium diode rectifies the pulses, which are smoothed out by a 1000 mfd capacitor and passed through the indicating meter.

This instrument is very versatile in that three different indications are possible: the flashing of a neon light, clicks in the headphones, or a reading on a meter. As with other counters of this general type, the instrument serves primarily as a detector of gamma rays.

Scintillation Counters

Some idea of the basic circuitry and mechanical construction of scintillation counters has been obtained from Chapter 5. These counters are somewhat more complex than Geiger counters, but still can be built in an amateur workshop. Expense is often a major deterrent — the crystal and photomultiplier tube are quite expensive. Aside from the crystal and photomultiplier tube assembly, construction is very straightforward and no more difficult than other electronic equipment having a comparable number of tubes.

Complete instructions for building a scintillation counter in the home workshop appeared in the April, 1955 issue of Radio & Television News.[7] An over-all view of this unit is shown in Fig. 6-16, and a complete schematic diagram is presented in Fig. 6-17. It is battery operated, readily portable, and suitable for airborne surveys or prospecting on foot or from moving vehicles.

A simple electronic high-voltage supply provides approximately 1000 volts for photomultiplier tube operation. A neon tube relaxation oscillator consisting of neon tube NE-2, capacitor C1, and resistor R1, produces pulses of a fairly constant amplitude at a frequency of about 100 cps. These pulses are impressed on the grid of V1, causing sharp pulses of plate current to flow through the reactor, which is the plate-circuit load. High-voltage pulses are produced by these sharp current changes, and are rectified by V2, which is connected as a diode. Tube V3 is a glow-discharge regulator tube which

---

*Available from U.S. Department of Commerce, Office of Technical Services, Washington 25, D.C.; Price 10¢.

7 Irving G. Snyder, A Portable Scintillation Counter, Radio & Television News, April, 1955, p. 35.

holds the output voltage constant at about 1000 volts. The polarity is negative with respect to ground.

In the detector assembly, the negative high voltage is impressed on the cathode of the photomultiplier tube. The final dynode is at ground potential, and the collector, or plate, is positive by about 22.5 volts. Each flash from the scintillating crystal causes a substantial pulse in the anode circuit of the photomultiplier tube. These pulses are coupled into the amplifier through capacitor C9.

Fig. 6-16. Over-All View of a Portable Scintillation Counter. Courtesy of Radio & Television News.

The pulses are amplified through tubes V4 and V5, and then coupled to V6, which is connected as a ratemeter circuit. Each pulse allows V6 to conduct momentarily in proportion to the amplitude. The voltage drop across R26 and R27 in the cathode circuit produces a deflection of the meter, thus giving an indication of the pulse rate and amplitude. To provide various ranges for the meter, it is merely necessary to control either the amplitude or frequency of pulses appearing on the grid of V6. Since the frequency is fixed by the radiation field being measured, the amplitude is varied by switching resistors R29 through R34 into the grid circuit, giving a total of 6 ranges. By proper calibration, with a pulse generator or other suitable source, the ratemeter circuit will indicate a range of frequencies from about 50 cps to 10,000 cps. The seventh position of SW2 places the ratemeter circuit in a no-signal state, permitting zero adjustment of the meter.

Since the ratemeter circuit is sensitive to pulse amplitude as well as pulse frequency, a master amplitude control P1 is provided,

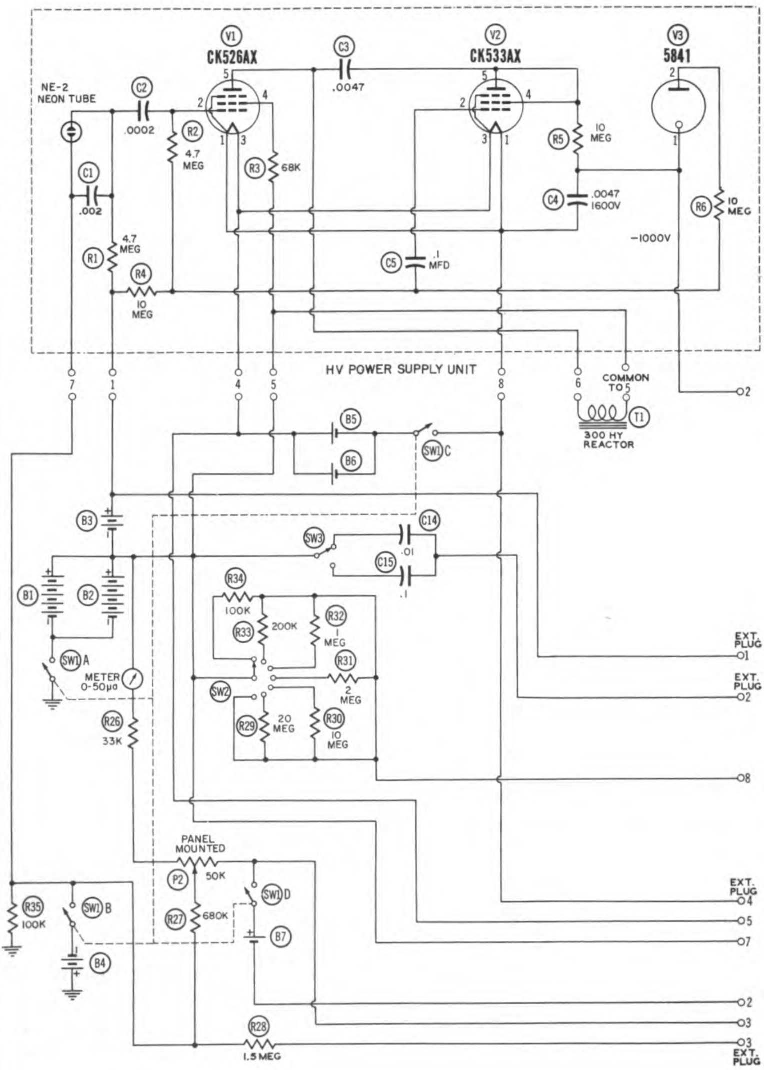
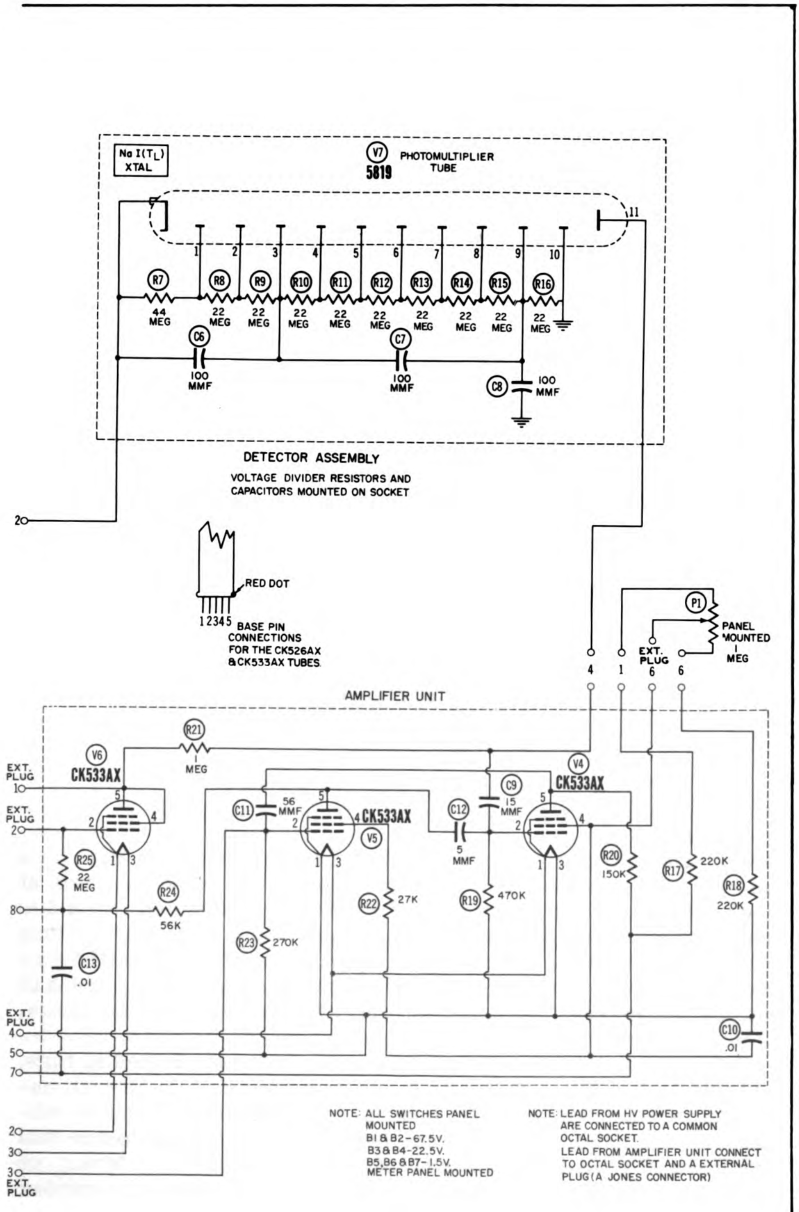


Fig. 6-17. Schematic Diagram of



Scintillation Counter Shown in Fig. 6-16.

which is an external control. It serves to vary the screen grid potentials of the two amplifier tubes V4 and V5, and so controls the output pulse amplitude.

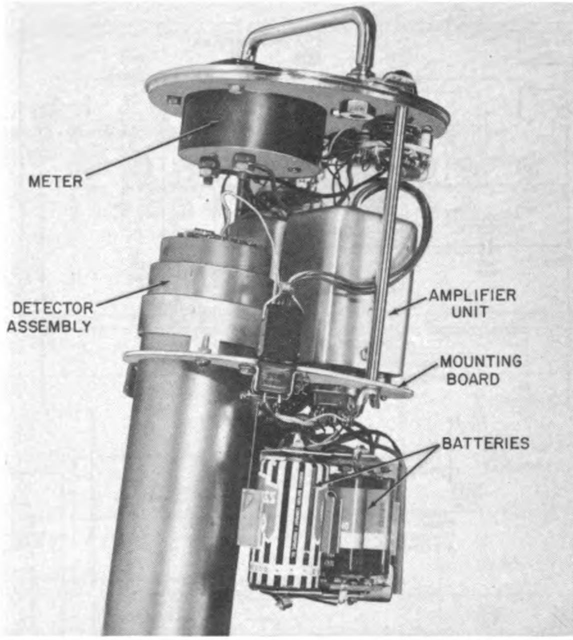


Fig. 6-18. Interior of Counter Shown in Fig. 6-16. Courtesy of Radio & Television News.

Nuclear radiation occurs at a random rate rather than at a fixed frequency, so the meter merely indicates the average rate at which pulses are being received. Switch SW3 selects either of two time constants for the meter circuit, providing either a long or a short averaging time. With the 0.01 mfd capacitor C14 in the circuit, meter response is quite rapid; switching in C15, a 0.1 mfd unit, increases the time constant and slows down meter response.

Mechanical construction of this instrument is indicated in Figs. 6-18 and 6-19. Although a round can was used for the overall enclosure in the original unit, a rectangular enclosure may be substituted. It must be remembered, however, that the enclosure will tend to shield the detector assembly from the rays being detected, so a light-weight material such as aluminum should be used, or a window inserted immediately beneath the detector.

This particular instrument was designed for aerial prospecting, so the detector assembly is somewhat larger than might otherwise be used. A 2" diameter crystal and 2 1/4" diameter photomultiplier tube are mounted inside a 20 gauge, 2 1/4" diameter steel

tube which serves as a magnetic shield as well as a mechanical support. For other types of prospecting, a 1" crystal and a photomultiplier such as the RCA 6199 would be satisfactory, and a smaller diameter cylindrical housing could be used. No other mechanical or circuit changes would be necessary. All resistors and capacitors used in the photomultiplier tube are conveniently mounted in the tube base, as can be seen in Fig. 6-19.

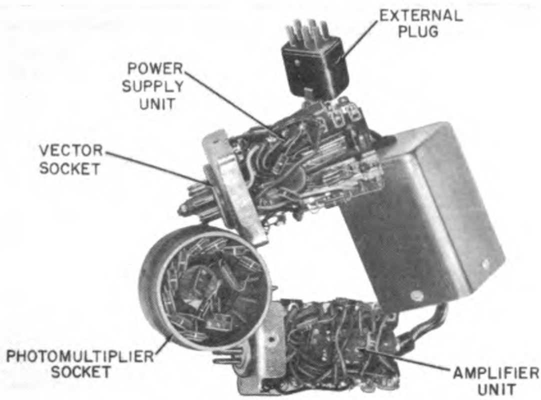


Fig. 6-19. Subassemblies Which Go to Make Up the Complete Counter of Fig. 6-16. Courtesy of Radio & Television News.

The power supply unit and amplifier unit are each mounted in a separate plug-in enclosure utilizing an octal socket. The general construction can be seen from Fig. 6-19. A sufficient number of terminals for the power supply unit is provided by the octal socket. In the amplifier, additional terminals are necessary and are provided by a 6-pin socket and plug-in assembly as can be seen in the photograph. The 6-pin plug and socket terminals are designated "EXT PLUG" in Fig. 6-17. All the other contacts for the amplifier assembly portion of the diagram are for the terminals of the octal socket and plug built into its base. The octal plug and socket terminals for the power supply section are indicated directly below the power supply portion of the diagram.

Inside the amplifier assembly, vertical terminal strips provide a means for making connections. The subminiature tubes are mounted over them. A cover over the assembly shields it from the oscillations produced in the power supply unit. Both units employ the same general type of construction.

All major subassemblies are mounted on a circular piece of phenol impregnated fiber board 6" in diameter, the layout of which is shown in Fig. 6-20. If the over-all enclosure is not circular, this terminal board should be cut to fit the enclosure used. The board is

held to the top assembly by long bolts and wing nuts, which are evident in Fig. 6-18. All batteries are grouped and mounted with suitable clamps immediately beneath the terminal board.

Material for the top assembly can be whatever is convenient — metal, wood, fiber, etc. — as long as sufficient mechanical strength is maintained. The top plate serves to mount the meter, controls, switches, and carrying handle. In the unit illustrated, a metal plate was used, turned to fit the circular enclosure. Such a procedure is unnecessarily costly unless the builder has access to a lathe.

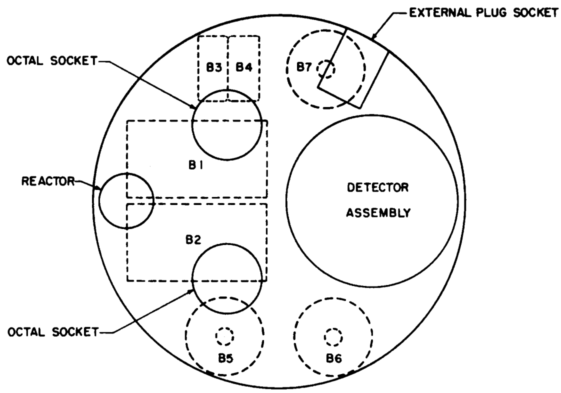
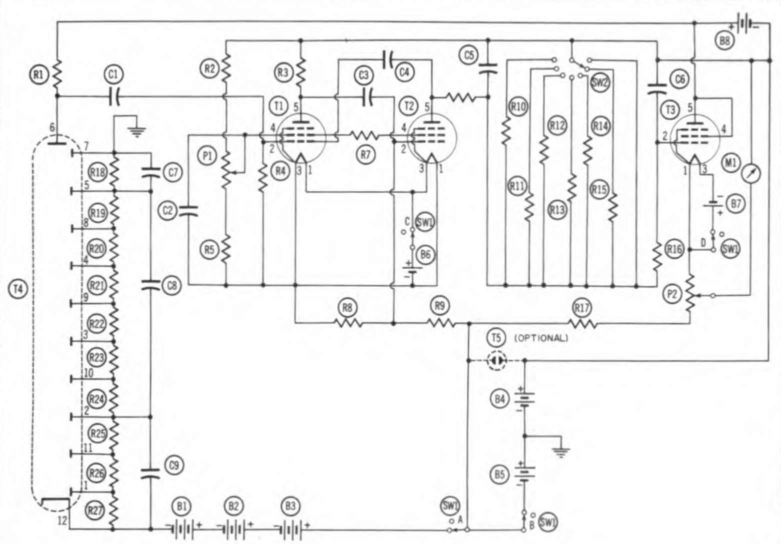


Fig. 6-20. Suggested Lay-Out for Circular Insulating Support.

Be careful in assembling the detector to make it light-tight and as shock resistant as possible. The thallium activated sodium-iodide crystal comes sealed in an airtight container with a transparent window to allow the light flashes to be transmitted to the photocathode of the photomultiplier tube. Follow the instructions which are contained with the crystal; they will usually call for a silicone oil or grease for sealing the crystal to the tube. Use Scotch No. 33 Electrical Tape around the tube envelope, the junction between the tube and the crystal, and the crystal itself. This tape will serve as a protection against shock and extraneous light, and will aid in mechanically supporting the assembly inside the detector enclosure. Since the entire assembly is mounted inside the over-all enclosure, no cap is necessary at the end of the steel detector tube.

This instrument is very versatile and will perform satisfactorily if properly constructed. However, the circuit can be simplified considerably by using batteries for the high voltage instead of the oscillator and rectifier arrangement described previously. Such a circuit is shown in Fig. 6-21, wherein the high voltage is provided by three special Geiger-counter batteries connected in series, giving 900 volts. Aside from the high voltage portion, the circuit is very similar to that of Fig. 6-17. Only three subminiature tubes are required.



CAPACITORS

C1 — .00015 Mfd.
C2 — .01 Mfd.
C3 — .00056 Mfd.
C4 — .0005 Mfd.
C5 — .01 Mfd.
C6 — .01 Mfd.
C7, 8, 9 — .0001 Mfd.
all 600 VDC

TUBES

T1, T2 — CK533AX
T3 — CK526AX
T4 — RCA 6199
T5 — P.L., NE51

RESISTORS

R1 — 1 Megohm
R2 — 220,000 Ohm
R3 — 150,000 Ohm
R4 — 470,000 Ohm
R5 — 220,000 Ohm
R6 — 27,000 Ohm
R7 — 56,000 Ohm
R8 — 270,000 Ohm-5%
R9 — 3.3 Megohm-5%
R10 — 20 Megohm
R11 — 10 Megohm
R12 — 2 Megohm
R13 — 1 Megohm
R14 — 200,000 Ohm
R15 — 100,000 Ohm
R16 — 22 Megohm
R17 — 470,000 Ohm
R18, 19, 20, 21, 22, 23, 24, 25, 26 — all 22 Megohm
R27 — 44 Megohm

BATTERIES

B1, 2, 3 — Eveready 493 (3), 300 volts.
B4, 5 — Eveready 455, 45 volts.
B6, 7 — Eveready D99, 1 1/2 volts.
B8 — Eveready 412, 22 1/2 volts.

METER

M1 — 0-50 Microamperes, full scale.

SWITCHES

SW1 A, B, C, D — all one switch. 4 circuit, 2 position, Mallory 3242J.
SW2 — Range switch. 1 circuit, 7 position. Mallory 31112J.

MISCELLANEOUS

Mount for T5 — Drake No. 101N.
Mounting Brackets and connectors for batteries are available where batteries are purchased.

Fig. 6-21. Simplified Scintillation Counter Using High-Voltage Batteries for the Photomultiplier Tube.

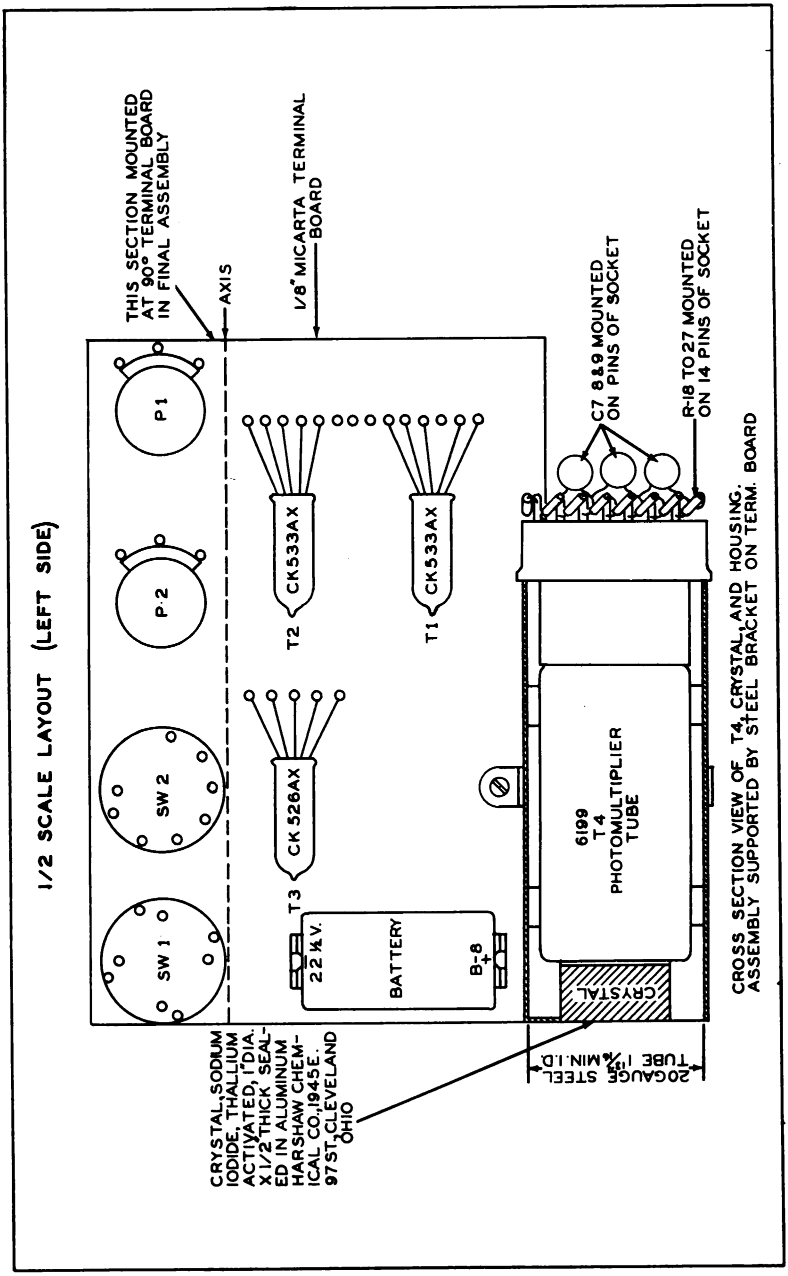
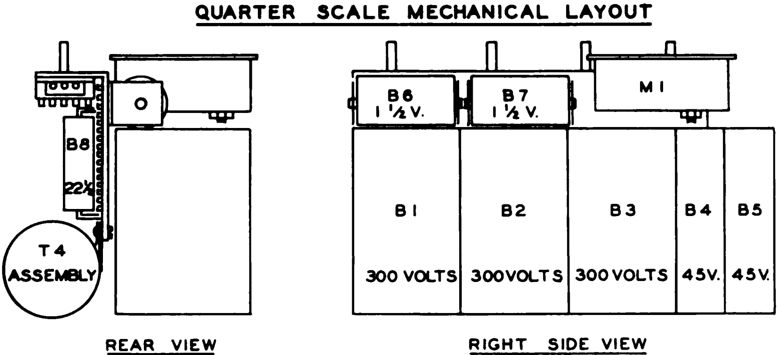


Fig. 6-22. Mechanical Drawing of Unit Using Circuit of Fig. 6-21. (Left Side)

A proposed mechanical layout for this type of construction is shown in Figs. 6-22 and 6-23. The detector assembly is mounted on the exterior of a rectangular metal case, and can be connected to the case by means of a flexible cable. This method of construction permits greater flexibility in the use of the device. Since the high-voltage battery drain is very small, these batteries should last as long in use as they would if stored on a shelf.



NOTES

1. Optical Coupling Fluid (Dow Chemical Co.) must be used to couple the glass window of the crystal package to the end of the 6199.
2. Sponge rubber strips should be used between the glass envelope of T4 and the steel tube shield.
3. The crystal should be held in place against T4 by SCOTCH Electrical Tape.
4. The electrical coupling from pin 6 of T4 to the grid of T1 should be kept as short as possible.
5. T1, T2, and T3 are Raytheon subminiature tubes and may be held in place by any suitable mechanical means.
6. All layouts are compactly designed and may be expanded to facilitate ease of assembly.
7. Any case, hardware, etc., may be used at the discretion of the assembler, but heavy walls must not surround the portion of the T4 assembly where the crystal is located.
8. P1 (not listed in components) is a 1 megohm potentiometer. It is the control used in the calibration of the instrument and therefore may be mounted as shown or inside the case on the terminal board.
9. P2 (not listed in components) is a 50,000 ohm potentiometer and is used in zeroing the meter. It must be mounted on the top of the meter panel along with the switches.

Fig. 6-23. Rear and Right Side Drawings of Unit of Fig. 6-21.

High-Voltage Supply

One of the problems encountered in designing either a Geiger or a scintillation counter is that of providing a suitable source of high voltage, on the order of 700 to 1000 or more volts at a few microamperes. One possible source is batteries, which are comparatively heavy; others include a vibrator or a vacuum-tube circuit of some kind, both of which are inefficient and wasteful of energy.

The August, 1954 issue of Electronics magazine contains an article[8] which describes a transistor-operated high-voltage supply

8 Alan R. Pearlman, Transistor Power Supply for Geiger Counters, Electronics, August, 1954, p. 144.

which will provide 700 volts at 5 microamperes from a 3-volt battery source. Total battery drain is about 3.6 ma, which may be provided by two size-D flashlight batteries, or two mercury cells rated at 3600 ma-hours each. With either source, battery life is about 1000 hours.

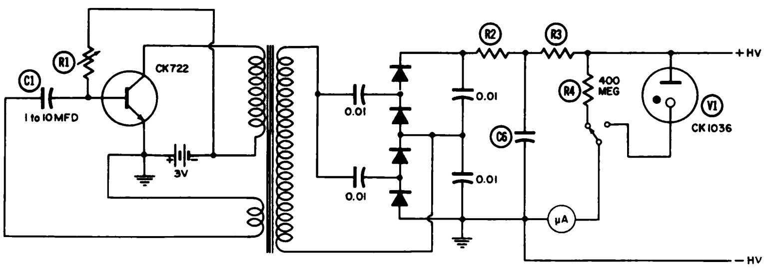


Fig. 6-24. Transistor-Operated High-Voltage Supply for a Geiger or Scintillation Counter. R1 is Adjusted to Obtain Proper Operating Point; R2 and R3 Can Be from 100,000 Ohms to 2.2 Megohms.

A circuit diagram of this unit is shown in Fig. 6-24. It consists of a class C transistor audio oscillator, a step-up transformer, rectifier, filter, and voltage regulator. Operating frequency is determined primarily by R1 and C1. In general, the oscillator will function well over a wide range of frequencies below the self-resonant frequency of the transformer. As a consequence, a fixed value of C1 may be used and R1 adjusted to the proper operating point.

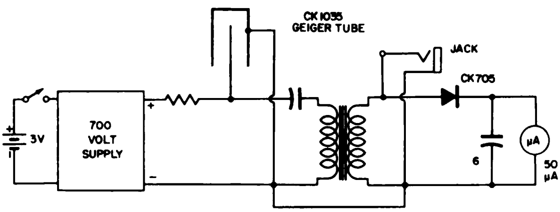
Transformer requirements cannot be met by commercially available units, so a special transformer was built for the circuit of Fig. 6-24. The primary consists of 600 turns with a DC resistance of about 10 ohms, and the 30,000 turn secondary provides a step-up ratio of 50 to 1. Losses in this transformer are extremely low.

A voltage quadrupler rectifier circuit using four small selenium units rectifies the secondary voltage and approximately quadruples the voltage available from the transformer. This arrangement permits efficient operation with collector supplies of as low as 3 volts.

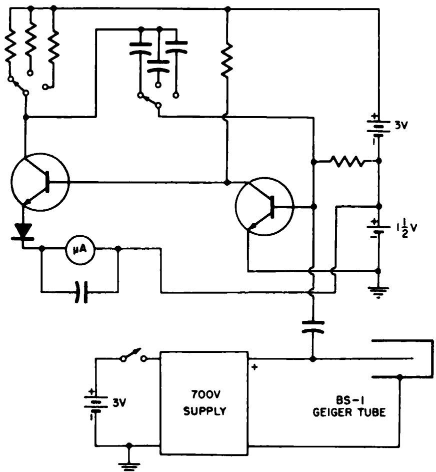
Filtering is provided by R2, R3, and C6. The resistors can be any value from 100,000 ohms to 2.2 megohms, and a small value of capacity for C6 provides adequate filtering. Capacitor C6 should, of course, have a voltage rating at least as high as the highest output voltage of the rectifier.

Regulation is provided by the CK-1036 subminiature regulator tube. For normal operation, either R2 or R3 is adjusted so that the

regulator tube operates satisfactorily without drawing excessive current. Such an arrangement holds the output voltage constant to within 15 volts over a considerable variation of load current.



A



B

Fig. 6-25. (A) Simple Geiger Counter Incorporating the Power Supply of Fig. 6-24. (B) Complete Geiger Counter with Three-Range Ratemeter Circuit Using n-p-n Transistors.

As an example of the efficiency of this device, it can provide an output of 6 microamperes at 700 volts with an input of only 10 milliwatts (3.33 ma at 3 volts) representing an efficiency of 42%. This compares with a requirement of at least 30 milliwatts just for the driving coil of a vibrator-type supply. The transistor supply permits more than a 10-fold increase in battery life.

A Geiger counter using no tubes other than the Geiger tube is shown schematically in Fig. 6-25A. Pulses are coupled to the primary of a step-down transformer, after which they are rectified by a CK705 crystal and passed through the indicating meter. Headphones may be employed to count the clicks if desired.

Maximum benefit can be derived from the use of transistors if they are also used in the amplifier and counting rate circuits. Such a circuit is shown in Fig. 6-25B. In addition to the transistor used in the power supply, two type n-p-n transistors are employed in a 3-range counting rate meter which requires only 4 milliwatts of battery power, less than 1/3 that required by the filament of a low-drain hearing-aid tube.

The foregoing discussion emphasizes very dramatically the role that transistors will play in the future development of radiation instruments.

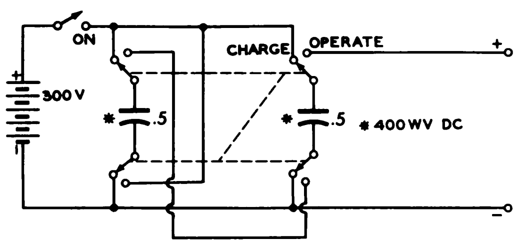


Fig. 6-26. System for Getting 900 Volts from a 300-Volt Battery.

Fig. 6-26 shows a switching arrangement with which it is possible to get 900 volts to apply to a counter circuit, using only a single 300-volt battery. First, the battery is used to charge up two capacitors to 300 volts, and then the battery and both capacitors are connected in series with each other for use. The switch in the circuit of Fig. 6-26 is shown in the charge position. Both capacitors are connected across the 300-volt battery when the switch at the top is set at "on." When the four section switch is set at "operate," the capacitors and the battery are all connected in series. This supply will operate a 900-volt Geiger tube for several minutes if you use a well insulated switch and high grade capacitors in the construction. The four section switch can be of the spring return type, so that it is only necessary to move it momentarily to the "charge" position and then let it return to the "operate" position for normal operation.

CHAPTER 7

Dosimeters

Subcommittee No. 7 of the Radio Electronics Television Manufacturers Association defines a dosimeter as follows: "A dosimeter is a device worn or carried by an individual to measure his accumulated exposure to nuclear radiation or x-rays." In general, a dosimeter depends for its operation on the effects of ionizing radiation on its sensitive elements. Construction varies depending on the methods used for gauging the magnitude of these interactions.

Some dosimeters are completely self-indicating, that is, they require no auxiliary apparatus for giving an indication of exposure. Others are self-indicating after they have been prepared for use by means of auxiliary equipment. Still others require indicating accessaries. Several different basic principles of operation are used, including effects on photographic film, chemical effects, photoluminescence, and ionization.

Film

Film dosimeters are widely used by the Atomic Energy Commission. They operate on the principle that ionizing radiation will

Fig. 7-1. Typical Film Badge Dosimeters. Courtesy of Tracerlab, Inc.

expose photographic film, the amount of exposure being approximately proportional to the incident radiation. Therefore, after exposure, the film can be developed and the film density will be a measure of the total exposure.

Typical film badges which can be worn on exterior clothing are shown in Fig. 7-1. These badges are worn for a certain period (a week, for example) and then returned to the manufacturer for processing. Here they are developed carefully and their densities are checked. If there has been an overexposure, the individual is notified immediately. Density comparisons are made against standard films which have been exposed to a known radiation dosage.

The Tracerlab radioactivity badges shown in Fig. 7-1 contain two films, a highly sensitive film for measuring dosages from 0 to 2 roentgens, and an insensitive film for dosages up to 30 roentgens. Part of the film is covered by a cadmium filter so that it will measure gamma and high energy x-ray dosages only, while the rest responds to beta and very low energy gamma radiation as well.

X-ray dosages can also be checked with a film badge. Tracerlab uses the same holder and film as in the radioactivity badges. However, since the density of the film blackening varies greatly with the voltage used to produce the x-rays, a graduated copper step wedge is provided to give an indication of the energy of the x-ray beam.

Nuclear-Chicago has a film badge service available. The "Nuclibadge" which is provided contains a high range "catastrophe" film. For most radiation energies, the film may be read for any exposure from 50 mr to 500 r. Accurate indications of personnel exposure are possible for all usual sources of ionizing radiation from 30 kev to 10 mev. An open window is included in the badge holder to estimate beta exposure.

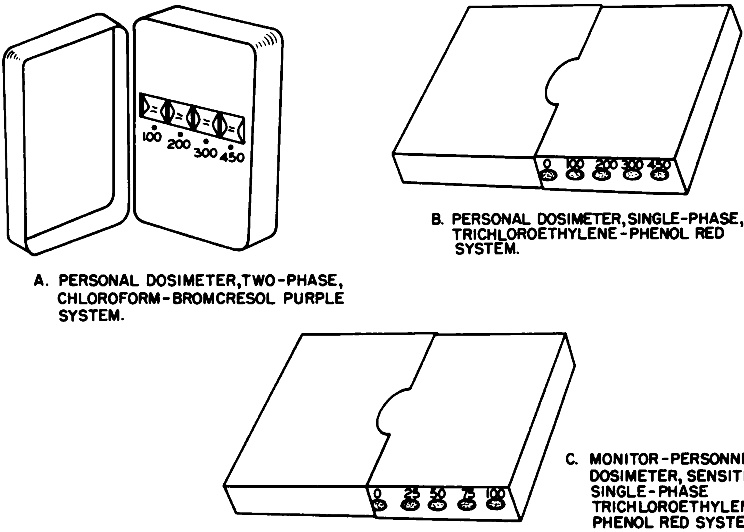
For work involving considerable finger and hand exposure, the Los Alamos Scientific Laboratory has developed a finger film badge. Eastman Type K or Dupont sensitive film is used. Brass and cadmium filters, 20 mils thick, provide selective absorption for increasing the range of measurement. The completed device can be worn on a finger under rubber gloves, does not hamper finger manipulation, is waterproof, lightproof, and is not affected by most solvents. Accurate determinations of beta, gamma, or x-ray exposure of the fingers can be made.

Chemical Dosimeters

Chemical changes which take place in some substances when exposed to radiation have been used to advantage in the development of chemical dosimeters. The most common reaction is the formation of an acid when a hydrocarbon such as chloroform is irradiated. Since the amount of acid formed is directly proportional to the amount of radiation absorbed, the problem is to measure the amount of acid present after exposure.

A common method of indicating acid content is to employ pH sensitive dyes which change color in accordance with the acidity of the solution in which they are dissolved. The pH of a solution is a measure of its acidity or alkalinity; a pH of 7 is neutral, a pH of less

than 7 indicates that the solution is acid, and a pH greater than 7 indicates an alkaline solution. For example, aqueous Phenol red shows red for a pH of 7.4 and yellow for a pH of 6.8.



A. PERSONAL DOSIMETER, TWO-PHASE, CHLOROFORM-BROMCRESOL PURPLE SYSTEM.

B. PERSONAL DOSIMETER, SINGLE-PHASE, TRICHLOROETHYLENE-PHENOL RED SYSTEM.

C. MONITOR-PERSONNEL DOSIMETER, SENSITIVE SINGLE-PHASE TRICHLOROETHYLENE-PHENOL RED SYSTEM.

Fig. 7-2. Typical Chemical Dosimeters.

A chemical dosimeter which saw wide usage during some of the atom bomb tests consists of chloroform to which a small amount of a chemical called resorcinol is added for stabilizing purposes. The indicating dye is added in various concentrations depending on the range of intensities to be measured. This results in a two-phase system (the dye solution does not mix with the chloroform). The material is placed in small glass ampoules which are then sealed. Four of these, having different ranges, are then assembled in an enclosure as shown in Fig. 7-2A.

Another type of dosimeter which has been widely tested is a single-phase system consisting of aqueous Phenol red saturated with redistilled trichloroethylene. The reagents are sealed in silicon-coated neutraglass ampoules and assembled into enclosures as shown in Figs. 7-2B and 7-2C.

Chemical dosimeters are essentially independent of the rate at which radiation is received, and so can be valuable in determining large doses of high intensity, short time exposure, as in a bomb explosion. During one series of tests, results indicated that response to gamma rays was uniform despite a variation of dosage rate of 5 to 1200 r/min. Chemical systems are also relatively independent of

radiation energy, uniform results being obtained with gamma rays having energy variations from 35 kv to 1200 kv.

Direct-reading chemical dosimeters have been developed which register gamma doses as low as 25 to 30 r. Incremental exposures of 10 r can be distinguished by use of appropriate color standards, and smaller exposures may be estimated by using equipment for detecting small color changes, such as the spectrophotometer.

Radiophotoluminescence

The principle of radiophotoluminescence refers to the phenomenon whereby a material which has been exposed to x- or gamma radiation becomes luminescent (gives off visible light) when irradiated by ultraviolet light. Silver-activated phosphate glass has this property, and has been used extensively by the Navy in the form of the phosphate glass dosimeter.

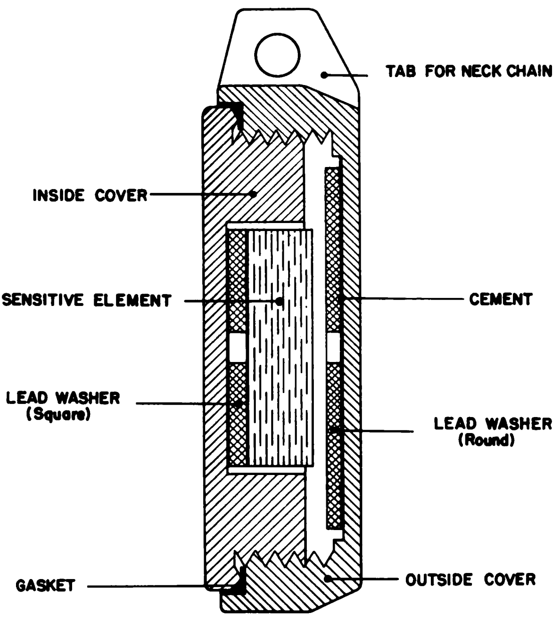


Fig. 7-3. Cross-Sectional View of a Radiophotoluminescent Dosimeter, the Model DT-60. Courtesy of Corning Glass Works.

A cross-sectional view of the DT-60 phosphate glass dosimeter is shown in Fig. 7-3. The sensitive element is a block of silver phosphate glass 3/4" square and 3/16" thick. Lead shields are added as shown to make response essentially independent of the energy of the incoming radiation. The case is made in two sections which are threaded to fit together, and a special tool is required for opening.

To read the amount of exposure, an auxiliary instrument is required. It consists of a source of ultraviolet light for illuminating the phosphate glass, and a means for determining the intensity of

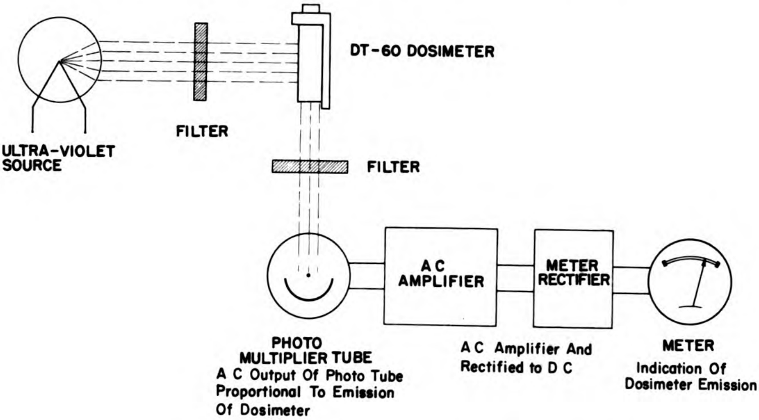


Fig. 7-4. Block Diagram of Method Used for Reading the Radiophotoluminescent Dosimeter. Courtesy of Corning Glass Works.

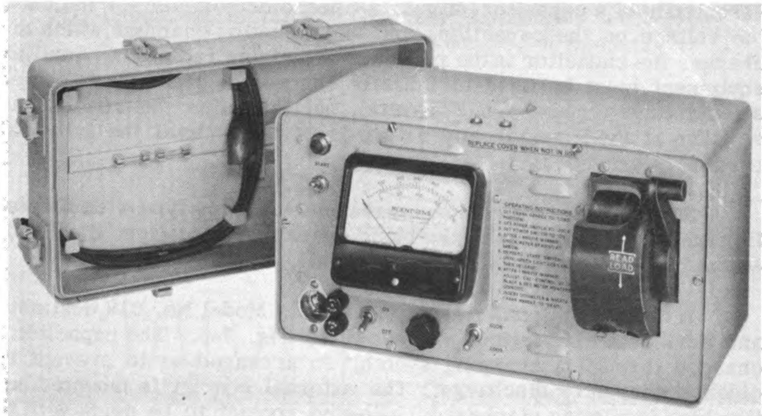


Fig. 7-5. Reader for Radiophotoluminescent Dosimeter. Courtesy of Specialty Engineering Div., Specialty Assembling & Packing Co., Inc.

visible light given off during such illumination. A block diagram of the basic system is shown in Fig. 7-4. A reader built by the Specialty Engineering Division of the Specialty Assembling & Packing Co., Inc. is shown in Fig. 7-5.

The phosphate-glass dosimeter has a number of distinct advantages over other types of dosimeters. It is extremely rugged; even though made of glass, it is very difficult to break when in its enclosure. Small cracks and chips in the glass do not affect accuracy of readings. Readings are linear regardless of time or rate of exposure, making calibration easy. The dosimeter may be read as many times as desired, since the reading process does not alter the glass in any way. The glass cannot be made to alter its reading or sensitivity by normal temperature or humidity conditions. It is conceivable that an individual could start wearing one of these dosimeters when he was born, and continue wearing it throughout his lifetime. Readings could be taken at any time he desired to know his total lifetime exposure by merely placing the device in a suitable reader. This results from the fact that the dosimeter will indicate the total accumulation of doses received at various intervals over a long period of time.

One disadvantage of the unit is its inaccuracy at lower dosages (about ± 50%). However, response is linear to at least 1500 r, and by special adjustments to the reader, exposures as high as 20,000 r can be read. Basic accuracy is within ± 20%.

Ionization Meters

Most popular of the direct reading type of instrument is the self-indicating ionization-chamber dosimeter. This device consists essentially of a capacitor, a quartz fiber electrometer for indicating the voltage on the capacitor, and an ionization chamber which discharges the capacitor in the presence of ionizing radiation. Auxiliary equipment must be used to initially charge the capacitor to the desired voltage (around 100-225 volts), but thereafter the reading may be taken at any time and any number of times until the full-scale reading is exceeded.

Several different companies manufacture this type of dosimeter. However, to get an idea of the basic operating principles, the Bendix Model No. 619 will be described in detail.

A cross-sectional view of the Bendix Model No. 619 dosimeter and a view of the reticle are shown in Fig. 7-6. The capacitor is charged through a charging switch, so arranged as to prevent accidental charge or discharge. The external contact is mounted on a flexible, insulating diaphragm, allowing contact to be made with the center terminal of the capacitor when pressed into the charger (to be described later), and disconnecting the capacitor when the unit is removed from the charger. Such an arrangement gives very high leakage resistance and the hermetic sealing allowed by such construction makes the dosimeter readings essentially independent of humidity and pressure changes.

A close-up view of the quartz fiber electrometer and ionization chamber is shown in Fig. 7-7. An incident photon (gamma ray) may knock an electron out of the wall of the ionization chamber. This

electron is attracted to the center positive terminal and serves to discharge the capacitor a slight amount. The rate at which discharge takes place is determined primarily by the intensity of incident radiation and the size of the capacitor.

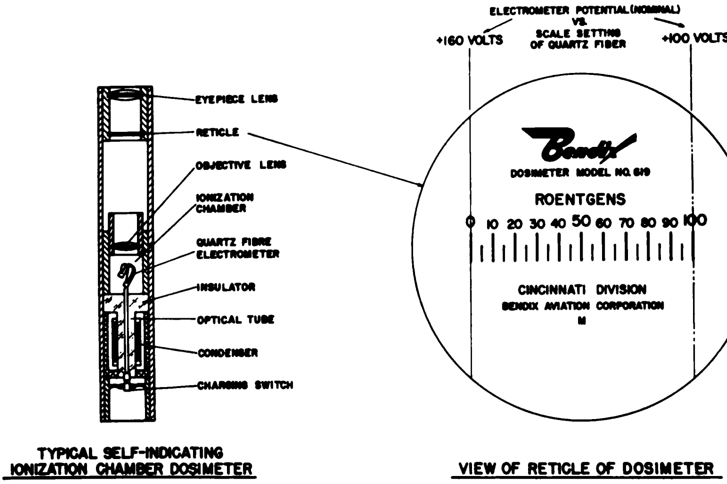


Fig. 7-6. Cross-Sectional View of Typical Self-Indicating Ionization Chamber Dosimeter and a Close-Up of the Reticle. Courtesy of Bendix.

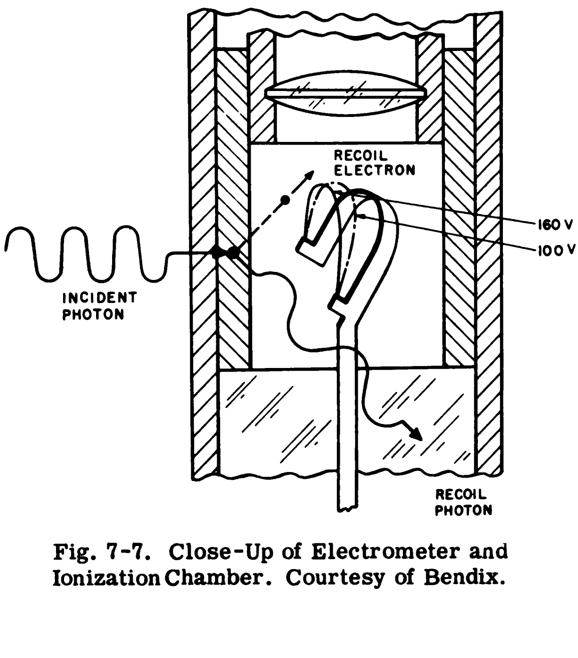
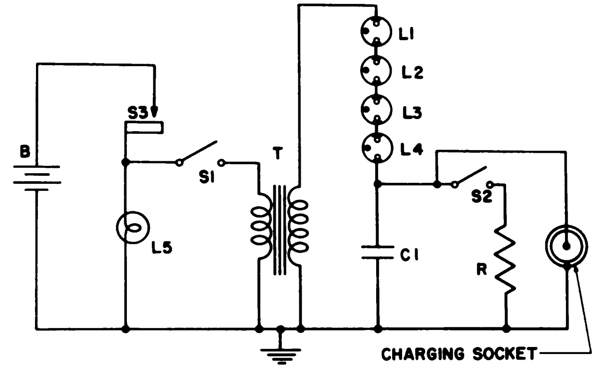


Fig. 7-7. Close-Up of Electrometer and Ionization Chamber. Courtesy of Bendix.

To charge this unit, a source of potential of approximately 140 to 180 volts is required. Fig. 7-8 shows a simple circuit which may be used for charging. A momentary contact switch S1 makes and breaks the primary current through T very rapidly, inducing a high voltage in the secondary. This voltage is rectified and regulated by a series string of four neon bulbs, and charges C1. The dosimeter capacitor is connected in parallel with C1 by means of the charging



B - 1.5 Volt Battery
S1 - Charging Switch (Momentary Contact)
S2 - Discharges Switch
S3 - Lamp Switch (Make Contact Only While Dosimeter is in Charging Socket)
C1 - Storage Capacitor
R - Leak Resistance
L1, L2, L3, L4 - Neon Bulb, NE2
T - Transformer
L5 - Lamp (For Illuminating Dosimeter)

Fig. 7-8. Circuit Diagram of a Typical Dosimeter Charger. Courtesy of Bendix.

socket. In practice, the dosimeter is inserted in the charging socket, automatically switching on lamp L5 which illuminates the scale. Switch S1 is operated a few times until the dosimeter electrometer indicates zero. The dosimeter is then removed from the socket and is ready for use. If the zero reading should be passed during the charging process, switch S2 may be operated to discharge the capacitor and bring the reading back to zero.

A single 1.5- volt battery provides the source of power for this charger. Current drain is very small, leading to long battery life.

Once charged, the dosimeter will indicate the total accumulated exposure from that moment until the next charging operation. Many different ranges of dosimeters may be built, variations being usually obtained by changing the value of capacitor. Ranges most commonly encountered are 0-100 and 0-200 mr. However, units are commercially available having ranges in excess of 0-2000 r. The Bendix Model No. 619, shown in Fig. 7-6, has a range of 0-100 r.

Pocket dosimeters of this type are usually about the size of a fountain pen, and so are easily worn. They are light in weight and can be read by pointing at a reasonably bright light. Recharging, although requiring special equipment, can be accomplished rapidly by relatively inexperienced personnel.

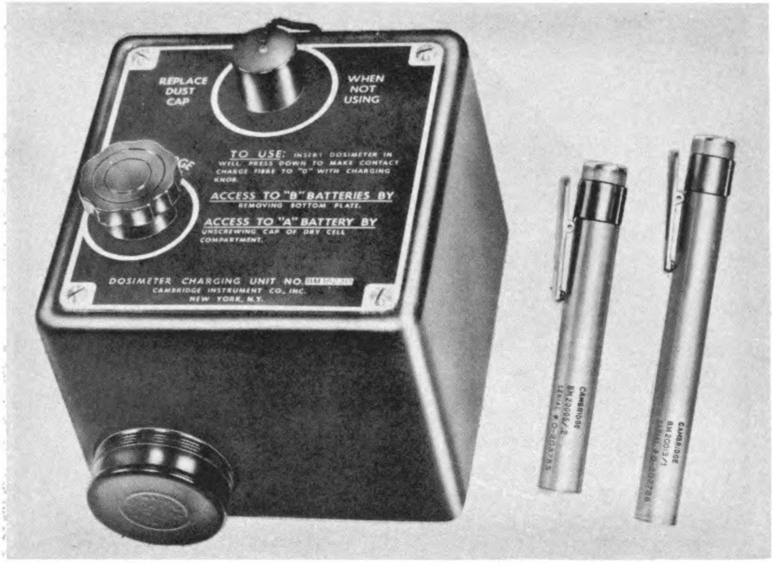


Fig. 7-9. Pocket Dosimeters and Charger for Gamma Ray Dosimetry. Courtesy of Cambridge Instrument Co., Inc.

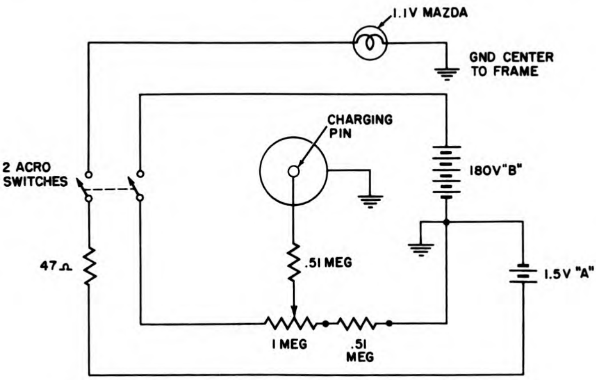


Fig. 7-10. Schematic Diagram of the Cambridge Dosimeter Charging Unit. Courtesy of Cambridge Instrument Co., Incorporated.

Another commercial version of this type of dosimeter is shown in Fig. 7-9, together with the charger. Made by the Cambridge Instrument Co., Inc., the dosimeters are available in ranges of 0-.2, 0-1, 0-5, 0-10, 0-50, and 0-100 r. In the photograph, the shorter unit has a range of 0-.2 r, and the longer a range of 0-1 r. All higher range units have the same length as the 0-1 r unit illustrated.

Fig. 7-11. A Victoreen Dosimeter and the Model 561 Charger. Courtesy of Victoreen Instrument Co.

A schematic diagram of the charging unit is shown in Fig. 7-10. Charging voltage is provided by a 180-volt battery and potentiometer arrangement, while light for illuminating the scale comes from a 1.1 volt lamp powered by a 1.5-volt battery. To operate the charger, the dosimeter is placed in the charging socket and the potentiometer varied until a zero reading is obtained. The unit is then withdrawn, and is ready for operation. There may be a slight loss of charge on withdrawal, so it is customary to overcharge the dosimeter enough to give an exact zero reading after it is withdrawn.

Figure 7-11 shows a dosimeter and charger made by The Victoreen Instrument Co. Dosimeters are available in ranges of 0-0.1, 0-0.2, 0-1, and 0-5 roentgens. Length is 4" and diameter 1/2", approximately the size of a fountain pen.

The charger will provide from 110 to 225 volts DC, and is powered by ten 22 1/2-volt batteries and one 1 1/2-volt battery. A light illuminates the scale when the dosimeter is plugged into the charging socket. A variable control is provided to adjust the voltage for setting the scale reading initially to zero.

Shown in Fig. 7-12 is the Tracerlab Model SU-8 pocket dosimeter compared with a fountain pen, and a cut-away view showing the interior construction. This particular model has a range of 0-100 mr, but additional scale divisions corresponding to 50 mr are provided at

both ends of the scale. Model SU-8H is also available, with a range of 0-200 mr. As with other instruments of this same general design, these dosimeters require an external charger, but can be read without auxiliary equipment of any kind except some illumination.

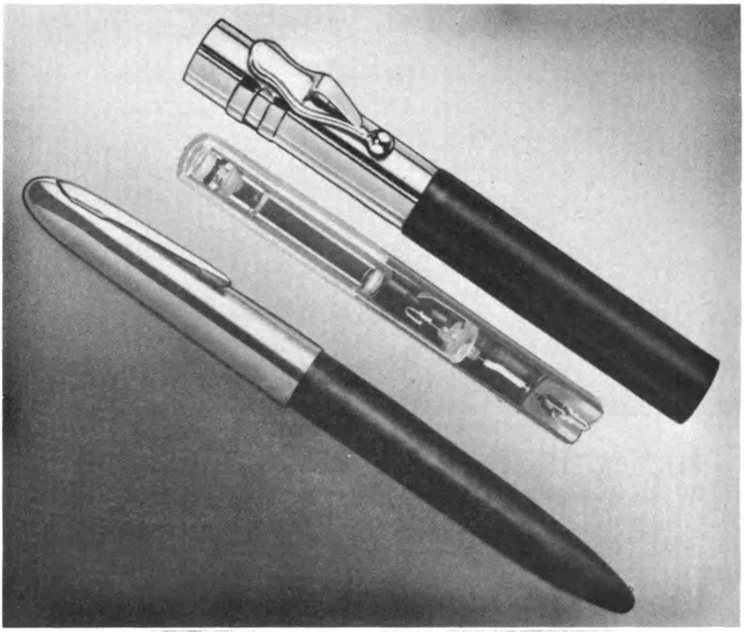


Fig. 7-12. Tracerlab Dosimeter Compared with a Fountain Pen, and Cutaway View of the Dosimeter. Courtesy of Tracerlab, Incorporated.

Figure 7-13 shows the charger, Model SU-9, in operation. Available voltage is adjustable from 120 to 240 volts by means of an external control. The power supply may be AC operated or may consist of eight 30-volt batteries and one "D" cell when portable operation is desired.

The charging switch on the dosimeter is operated by a magnet installed in the charger. This arrangement provides fool-proof operation, spring loading preventing accidental discharge, and permitting a type of construction which holds leakage to less than 2 mr per day. Accuracy is ± 5% of full scale, and the optical system permits reading the scale to within one mr. The low leakage makes it possible to use the instrument for several weeks without recharging it and to obtain an accurate cumulative dosage reading over a long period of time.

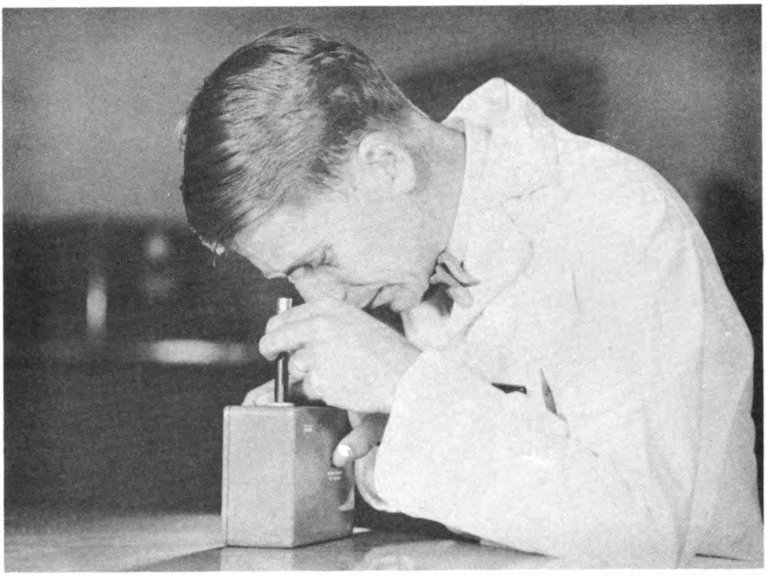


Fig. 7-13. The Tracerlab Dosimeter Charger, Model SU-9, in Operation. Courtesy of Tracerlab, Inc.

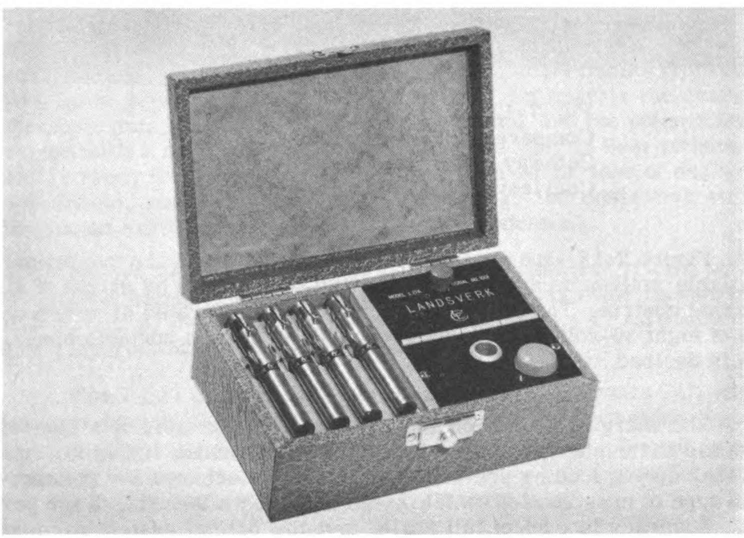


Fig. 7-14. The Landsverk Dosimeter and Charger Kit, Model L-21K. Courtesy of Landsverk Electrometer Company.

A dosimeter kit manufactured by the Landsverk Electrometer Company is shown in Fig. 7-14. The kit is designed for users who need only a few dosimeters, and includes the charger and four units

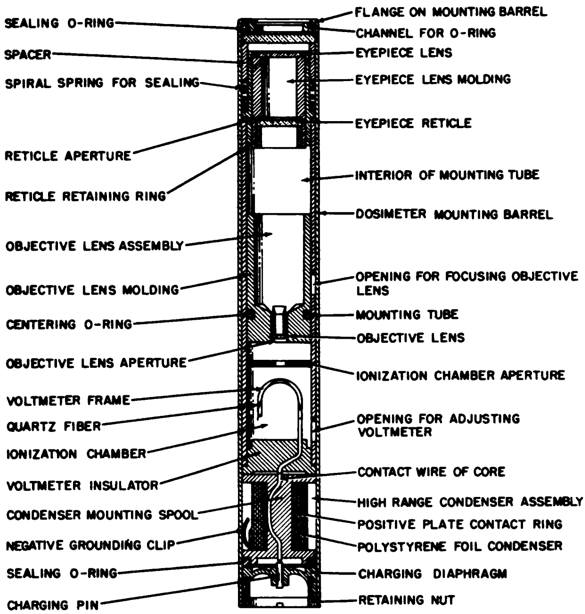


Fig. 7-15. Cross-Sectional View of a High-Range Dosimeter. Courtesy of Landsverk Electrometer Co.

of any desired range. Available ranges include 0-200 mr, 0-200 mrem, 0-5 r, 0-10 r, 0-20 r, 0-50 r and 0-100 r. The 0-200 mrem unit is somewhat unusual in that it will read equivalent exposure to thermal neutrons as well as to x-rays and gamma rays.

The charger will service any of the self-reading dosimeters in the Landsverk line. It is battery operated for complete portability, and contains only one control, a potentiometer for "zeroing" the dosimeter. A single size D cell provides 200 volts of filtered output at a battery drain of 100 ma. Since no current flows except during the brief charging operation, one cell will last for hundreds of charges. When a dosimeter is inserted into the charging socket, the switch for the socket lamp and for the potential circuit operates automatically.

A transparent plastic diaphragm supports a contact pin in a recessed position at the lower end of the dosimeter barrel. This construction permits the unit to be charged without exposing the interior to dirt and lint, thus holding leakage to a very low value. A detailed cross-sectional view of the high range dosimeter is presented in Fig. 7-15. Construction of the low-range units is very similar.

Another class of equipment called the "Roentgen Dose Meter" or "Condenser r - Meter" illustrated in Fig. 7-16, is also manufactured by Landsverk. In this type of instrument, the dose meter or pocket chamber contains a capacitor and ionization chamber, but no electroscope. The capacitor is charged on the auxiliary equipment, and when a reading is desired, the unit must again be plugged into the auxiliary charger-reader, at which time the voltage on the capacitor is read by a quartz fiber electrometer built into the charger-reader.

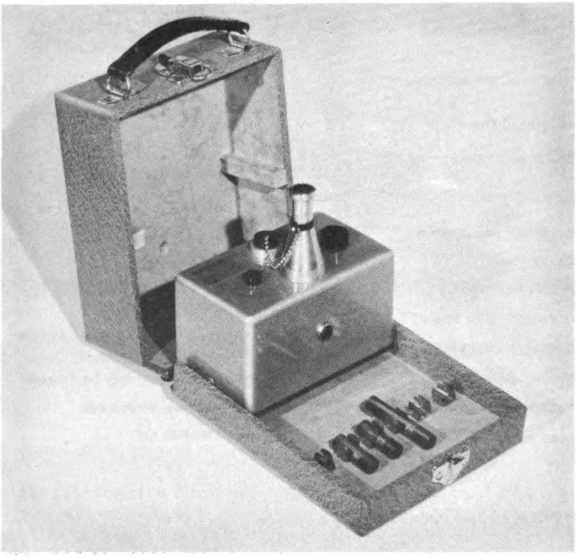


Fig. 7-16. Roentgen Meter or "Condenser R-Meter" Kit. Courtesy of Landsverk Electrometer Company.

Although not as convenient to use as the direct-reading dosimeter, the pocket chamber can be made smaller and more rugged, since it does not have to contain a quartz fiber electrometer or optical system. Since the input impedance of the charger-reader is very high, the chamber voltage (calibrated in mr or r) can be read a number of times before the capacitor needs re-charging.

Full-scale ranges of 0.5 r, 5.0 r and 50 r are available, and each unit is matched individually to the charger-reader for an accuracy of ± 2%. Calibrations are essentially energy-independent from 120 kev to 1400 kev. A calibration curve is provided to give the required correction factor when the chamber is used with rays having an energy of 20 kev to 130 kev, greatly increasing the versatility.

Another type of indirect-reading pocket chamber and charger-reader is the Minometer, made by Victoreen. The complete unit is

illustrated in Fig. 7-17. As with the Landsverk system described in the foregoing, the pocket unit consists of a capacitor and ionization chamber. The capacitor is charged on the charger-reader, and after exposure, the voltage on the capacitor is read on the built-in quartz fiber electrometer of the Minometer. Scale calibration is in roentgens of exposure, permitting fast, quick readings to be made.

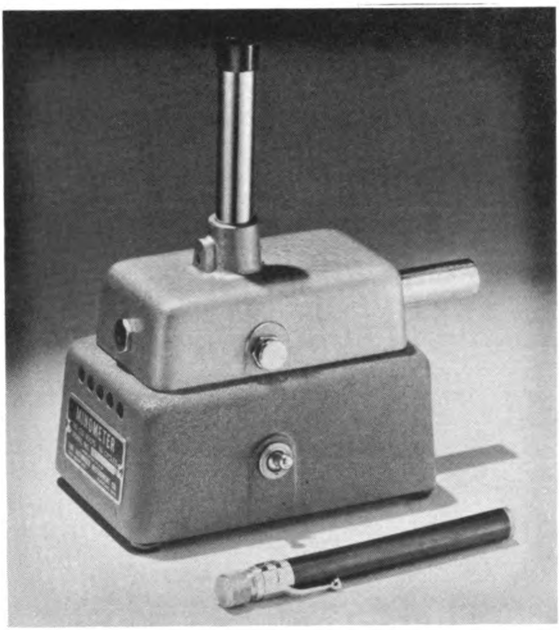


Fig. 7-17. The Victoreen Model 287 Minometer and Pocket Chamber. Courtesy of Victoreen Instrument Co.

A display kit, including a wide range of direct-reading dosimeters and pocket chambers, made by Landsverk, is illustrated in Fig. 7-18. Most of the units shown are sensitive to x-rays and gamma rays, but a few are sensitive to thermal neutrons and so are calibrated in mrem instead of mr or r.

A dosimeter which is both direct-reading and self-charging was described in the October, 1954 issue of Phillips Technical Review, published by Phillips Research Laboratories, Eindhoven, Holland. Basically it contains a friction charging device and a metal foil electroscope connected to a small ionization chamber. It is hermetically sealed in a glass enclosure, so that any desired pressure may be maintained in the chamber. Leaves of the electroscope serve as pointers, the actual meter scale is impressed on a piece of frosted glass. A magnetic charging switch is incorporated, and a cylindrical lens permits reading the scale at some distance.

Two complete units are shown in Fig. 7-19. The one at the right has a cylindrical magnifying lens, and the one at the left has a flat window. The size of the entire unit can be seen by comparison to the centimeter scale (0 to 13 cm) along the edge of the slide rule at

Fig. 7-18. Display Kit Showing a Variety of Dosimeters and Pocket Chambers. Courtesy of Landsverk Electrometer Company.

the right hand side of the illustration. There is a slide switch on the front of each instrument. This moves a permanent magnet inside the case, which operates a charging switch inside the sealed glass enclosure. This system prevents accidental discharge. Fig. 7-20 is a view of the charger and electroscope which has been removed from its aluminum case.

An interesting aspect of this device is the self-charging arrangement. The charger consists of a short, hollow tube in which a drop of mercury has been inserted. At one end is a lead connected to the electroscope. When shaken vigorously, the drop of mercury acquires an electrostatic charge which is transferred to the lead sealed in the tube and so charges the electroscope. Once charged, the unit will stay charged for as long as a month if not subjected to radiation. The charger can generate roughly 3000 volts with no current drain. When generating 2500 volts, a deflection of about one centimeter will be produced.

This device can be made very small and compact, about the size of a fountain pen, and can be easily clipped onto the clothing. Units have been made with various sensitivities; full-scale deflections of 0.2 r, 70 r and 250 r are readily obtainable.

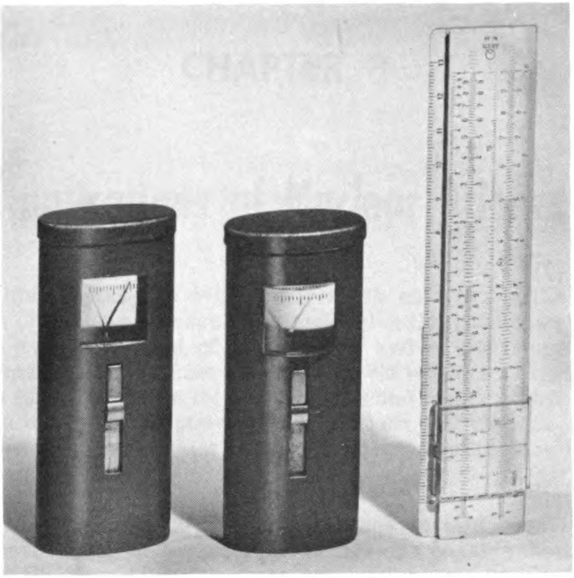


Fig. 7-19. Pocket Dosimeters With Built-In Chargers. The Model on the Right is Fitted with a Cylindrical Lens Window Which Acts as a Magnifier. Courtesy of Philips Technical Review.

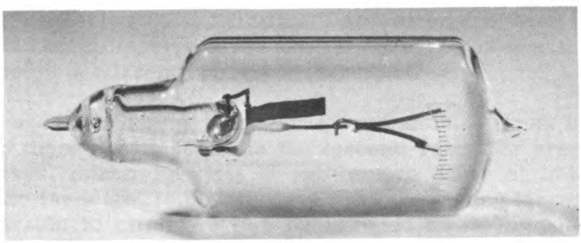


Fig. 7-20. The Electrostatic System of the Pocket Dosimeter. Courtesy of Philips Technical Review.

Conclusion

A dosimeter which can be worn by a person working in the presence of radioactive materials provides an easy method of determining total dosage. Usually two dosimeters are worn as a check on

each other — one can be a film type, and the other one of the direct or indirect-reading types described in this chapter. Although dosimeters have reached an advanced state of development, research is continually going on, and it can be expected that further improvements will be made as these devices come into more widespread use.

CHAPTER 8

Applications of Nuclear Science

In this chapter, we will merely touch on a few of the many applications of nuclear science. This will give the reader an idea as to the enormity of the field of applications and of the tremendous potential remaining for further expansion. We will discuss briefly such industrial applications as thickness gages and radiography. Then we will take a brief look at power generation and nuclear reactors. Finally, we will discuss just a few of the many applications for radioactive isotopes.

Our object in discussing applications in this book is to get a more rounded idea of the science of nuclear physics than we would get by merely examining measurements and measuring devices. The reader is cautioned against thinking that the vast field of application is limited just because this discussion is short. By rights, if we were to treat the subject adequately, this should be by far the longest chapter in the book.

Nuclear science has already penetrated many fields of endeavor, and it is still in its infancy. The recent completion of the atomic-powered submarine "The Nautilus," and extensive work now being carried out on nuclear-powered aircraft are two of the more publicized items of current interest.

In any work dealing with atomic radiation, it must be borne in mind that there is always some background radiation present due to cosmic rays, minute amounts of radioactive material in the atmosphere, and the slight radioactivity of the surrounding terrain. Where it is desirable to eliminate this background as far as possible, extensive shielding is employed. Lead is the most common shielding material. Often it is possible to arrange directional detectors which will record only that radiation coming from a particular direction. This can minimize background interference. Many applications not concerned with the background-initial adjustments ignore or cancel it out. Usually it does not vary enough during the period of measurement to introduce any discrepancies. Occasionally, however, the background varies enough to disrupt delicate measurements. Such variations may be due to atomic or hydrogen bomb tests anywhere in

the world — in fact, one method of determining when and approximately where such tests have taken place is to record the general background level in various areas. A significant increase in such level usually indicates nuclear tests of some kind.

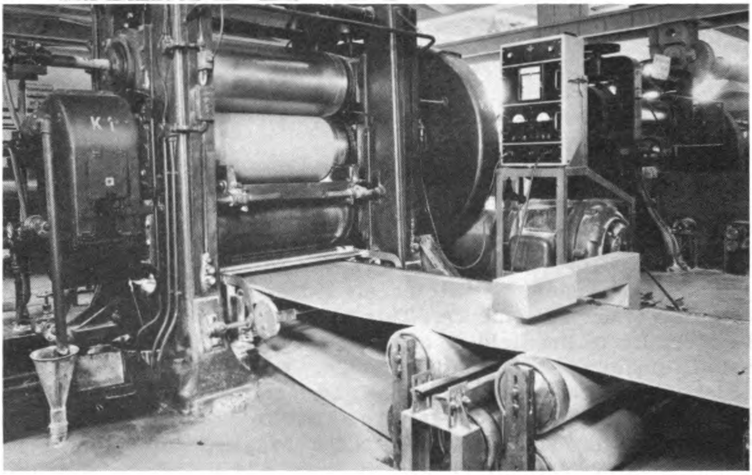


Fig. 8-1. Typical Installation of Beta Thickness Gage in a Paper Mill. Courtesy of Curtiss-Wright Corporation.

Thickness Gages

One type of device employing atomic radiation which has found wide application in industry is the beta thickness gage for continuous non-contact measurements of weight per unit area or thickness. It is based on the principle of the absorption of beta rays emitted by radioactive isotopes. Such absorption depends directly on the weight per unit area of the material through which the rays pass. If the density is constant, absorption is proportional to the thickness of the material.

To get a better idea of how such gages operate, we will describe a commercial unit made by the Electronics Division of the Curtiss-Wright Corporation. The unit, known as a beta gage, is shown in Fig. 8-1 in a typical paper mill installation. The block diagram of Fig. 8-2 shows the simplified circuit, and will be used to explain the operation.

A sealed source of beta radiation is positioned over or under the material to be measured, and an ionization chamber located directly opposite. Some of the rays are absorbed by the material and the remainder enter the ionization chamber. As the weight per unit area is increased, more radiation will be absorbed by the material and less will reach the ionization chamber. Radiation entering the ionization chamber causes an ionization current to flow through a load

resistor. This current is thus a function of radiation entering the chamber. The resulting voltage drop across the resistor will indicate the thickness of the material if its density is constant.

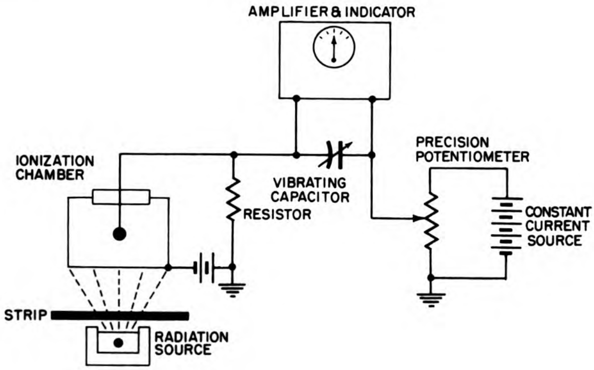


Fig. 8-2. Simplified Circuit of Beta Gage Showing Basic Principles of Operation. Courtesy of Curtiss-Wright Corporation.

Fig. 8-3. Close-Up of the Beta Gage Showing Location of Radioactive Isotopes. Courtesy of Curtiss-Wright Corporation.

A precision potentiometer is used to obtain a reference voltage which corresponds to the desired weight per unit area. Any difference between this reference voltage and the voltage across the load resistor then represents a deviation from the standard in the material being measured. When such a difference voltage is present, it is converted to AC by a vibrating capacitor, amplified, and used to operate a recording pen and deviation-sensing relay. The deviation signal may

then be used to operate auxiliary equipment, such as indicator lights, warning buzzers, and automatic controls.

Location of the source of beta radiation can be seen in the close-up view of Fig. 8-3. The isotope employed as a source depends on the thickness of material being measured. For example, thallium 204 can be employed for weights up to 100 mg/cm^2. Strontium 90 extends the range up to 500 mg/cm^2 and has the additional advantage that it lasts about 25 years. Thallium has a useful life of about 4 years. For still higher weights (to 2300 mg/cm^2, or 140 oz/sq. yd.) radium is used. With radium it is possible to measure the thickness of steel from 0 to 0.1185 inches. In some commercial instruments, cobalt 60 is employed.

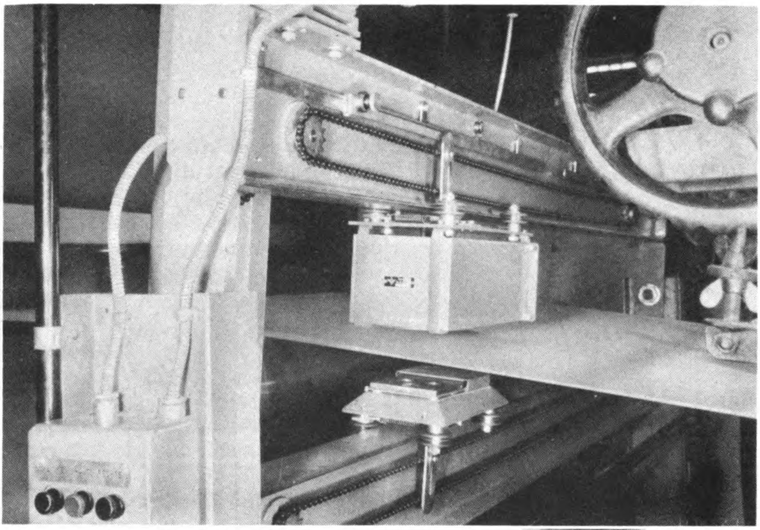


Fig. 8-4. Traverse Mounting of Beta Gage.
Courtesy of Curtiss-Wright Corporation.

If the instrument is calibrated once a day, the accuracy obtainable usually exceeds that attained from the production equipment. For example, using thallium, a sheet weighing 1 mg/cm^2 can be measured accurately to $\pm$ 0.05 mg/cm^2. For a sheet weighing 10 mg/cm^2, accuracy is approximately $\pm$ 0.1 mg/cm^2. In most cases, automatic calibration can be provided if required.

Many times it is desirable to know the weight per unit area over the entire profile of the material to be measured. For this use, a special traversing unit, such as the one shown in Fig. 8-4, is employed. If differential measurement is desirable, two or more recording heads can be installed, with the recording device arranged to indicate the difference between the heads and so give a measure of the

thickness of the material being added. Such an arrangement is shown in Fig. 8-5. Installations of this kind are particularly useful in all kinds of coating applications, such as coating glue on paper in the preparation of sandpaper. Often the savings in materials resulting from such measurements pays for the installation in a short time.

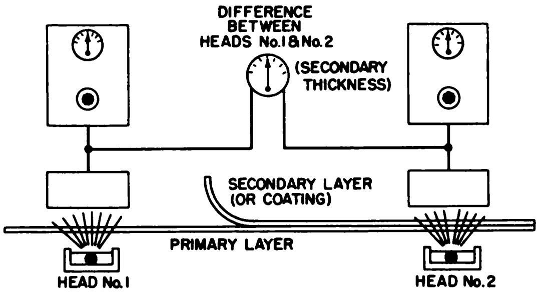


Fig. 8-5. Beta Gage Installation for Measuring Differential Thickness. Courtesy of Curtiss-Wright Corp.

One of the recurrent problems in industry is that of measuring the thickness of a coating laid over a base metal, such as tin over steel. Transmission gages of the type previously described can be used if the metal is not too thick, but a better method is to make use of the so-called "backscattering" principle.

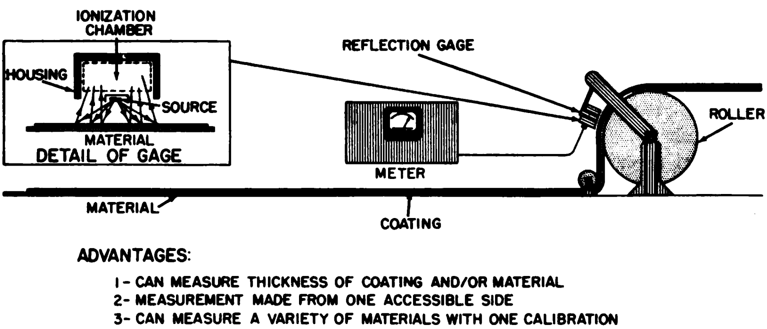


Fig. 8-6. Diagram of Thickness Gage Using the Principle of Backscattering. Courtesy of USAEC.

The diagram of Fig. 8-6, prepared by the Atomic Energy Commission, shows the basic principles of the backscattering thickness gage. Radiation from the radioactive material is directed at the coated strip and the reflected beam is measured by means of an ionization chamber. The change in reflected intensity is proportional to the coating thickness. If a steel roller is used, this technique can be employed to measure the thickness of paper, rubber, or a plastic sheet.

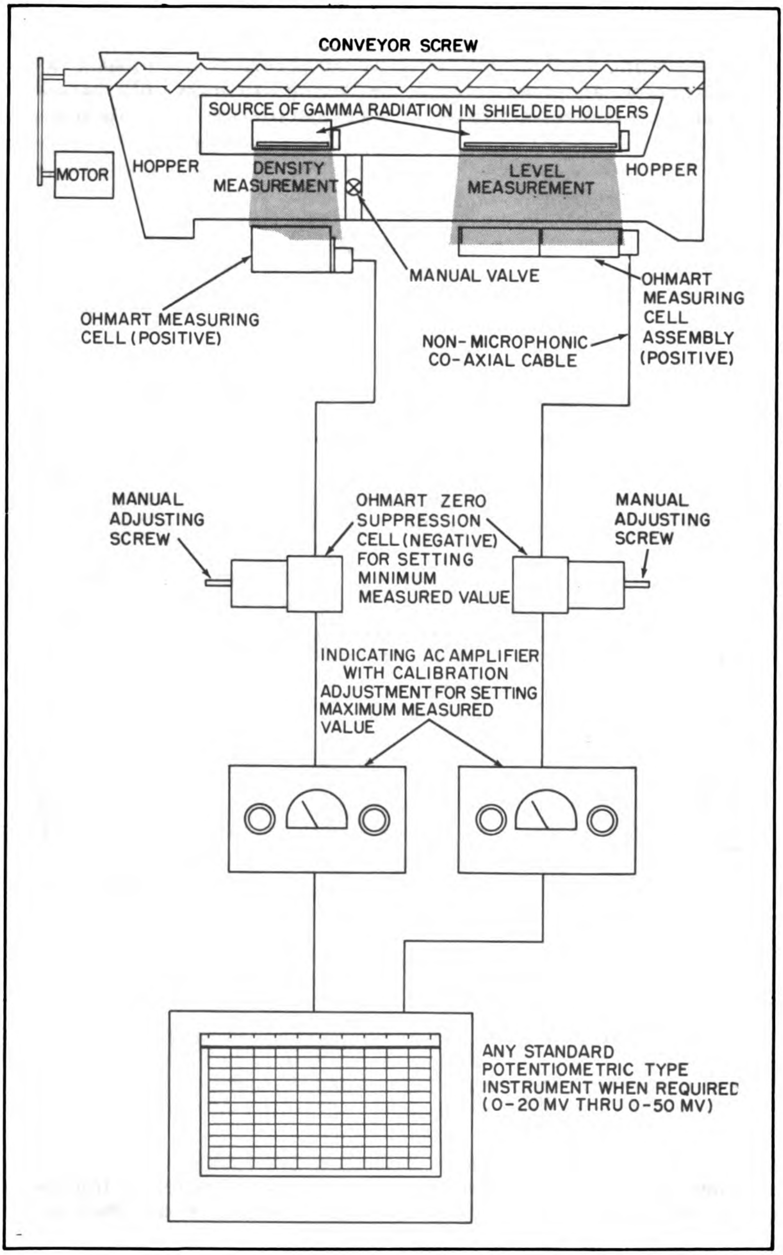


Fig. 8-7. Block Diagram Showing Basic Operating Principles of the Ohmart Density and Level Measuring Gages.

Density Gages

Another application c. :adiation absorption is the level or density gage, shown in its simplest fc-m in Fig. 8-7. It consists of three parts — a radioactive source, a detector, and an indicating instrument of some kind. The Ohmart Corporation has developed this type of gage commercially, and Fig. 8-8 shows a typical application of the commercial unit.

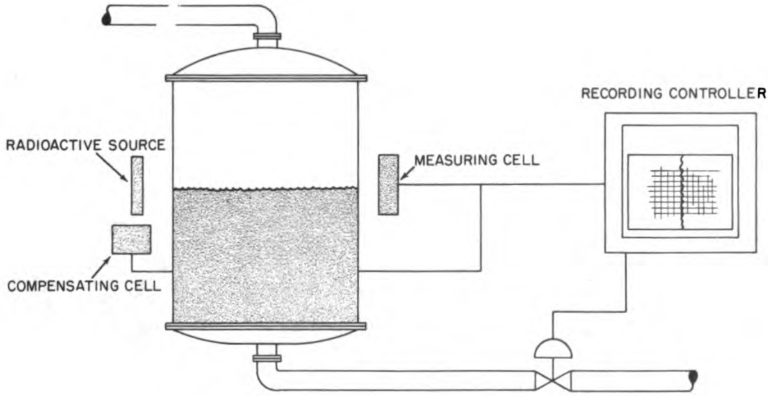


Fig. 8-8. The Ohmart Liquid Level Gage.
Courtesy of the Ohmart Corporation.

The Ohmart density gage makes use of a special cell which produces a current when exposed to radioactivity. This current varies as a function of the amount of radiation received by the cell, and is not dependent on any external high-voltage electrical source. In other words, the cell is in reality an atomic battery. The output of this cell is amplified as desired, and may be used to operate a recorder or meter.

Because of their greater penetrating power, gamma rays are employed in this density gage, and radioactive isotopes giving a suitable gamma ray output are necessary. Cesium 137 and cobalt 60 have been found satisfactory for the majority of applications. The actual amount of radiation required can be kept to very small values, minimizing the health hazard.

Flaw Detectors

A large and growing field of application of atomic radiation is in the field of industrial radiography, or flaw detection. Basically, the process consists of irradiating the object under investigation with a source of gamma rays, and using a photographic plate to record the variations in gamma ray transmission through the object. A careful study of the photograph then will reveal whether or not any flaws are present.

A great many companies are using this technique for the nondestructive evaluation of the internal quality of metal products. High-intensity x-rays are frequently employed for this purpose, but the increased availability and reduced price of radioactive isotopes has resulted in gamma ray sources which are cheaper and more convenient to use than expensive, bulky x-ray machines. Cobalt 60 appears to have wide applications in this field.

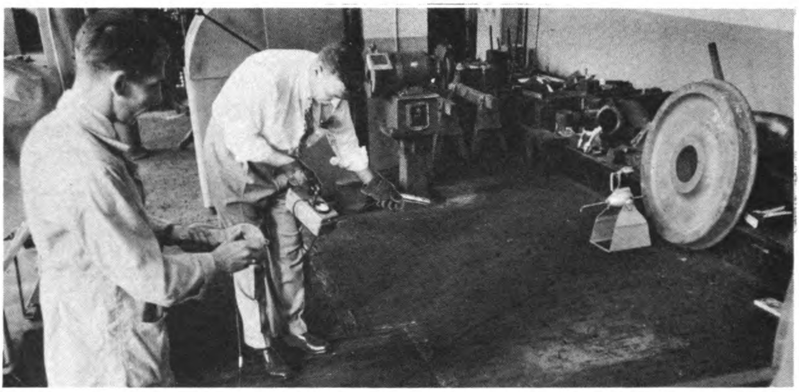


Fig. 8-9. Using Cobalt 60 for the Nondestructive Testing of a Railroad Car Wheel. Man in Center is Checking Level of Radioactivity with a Geiger Counter. Courtesy of Baltimore and Ohio Magazine.

Considerable experimental work along these lines has been carried out by the Baltimore and Ohio Railroad on both ferrous and non-ferrous castings. In practice, a cassette containing the desired type and size of industrial x-ray film is attached by some means to the object under investigation and the radioactive isotope brought into position on the opposite side so that the gamma rays will penetrate the material and expose the film. Any defects present will be visible on the film after development. Determination of exposure time for a given set-up depends on the strength of the isotope, thickness and density of material under investigation, type of film, and source-to-film distance. These factors can usually be calculated in advance.

An over-all view of an experimental set-up is shown in Fig. 8-9. The radioactive source is in place in front of a railroad car wheel, and the film is out of sight behind the wheel. Because this work is all experimental in nature, a careful check of radioactivity in the immediate vicinity is made with a Geiger counter. Thus, any danger to personnel becomes immediately apparent. A close-up of the radioactive source, wheel, and Geiger counter is shown in Fig. 8-10.

The basic principles involved in industrial radiography using isotopes are indicated in Fig. 8-11. In addition to cobalt 60, which

is employed most extensively in this type of work, cesium 137 and iridium 192 are widely used. It is interesting to note that the penetrating power of a millicurie of Co^{60} is about 50% greater than the same quantity of radium.

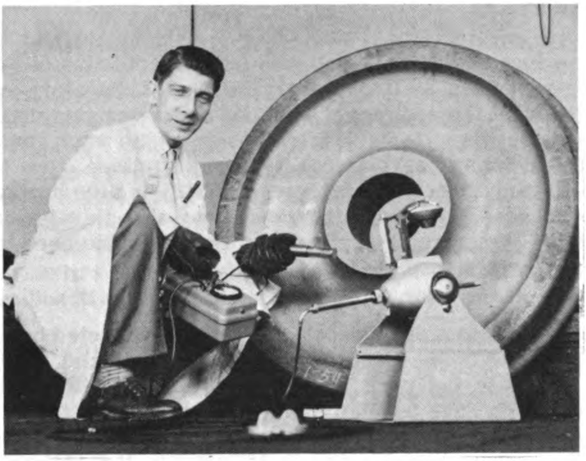


Fig. 8-10. Close-Up of Arrangement Used for Radiographic Testing for Flaws and Measuring Level of Radioactivity. Courtesy of Baltimore and Ohio Magazine.

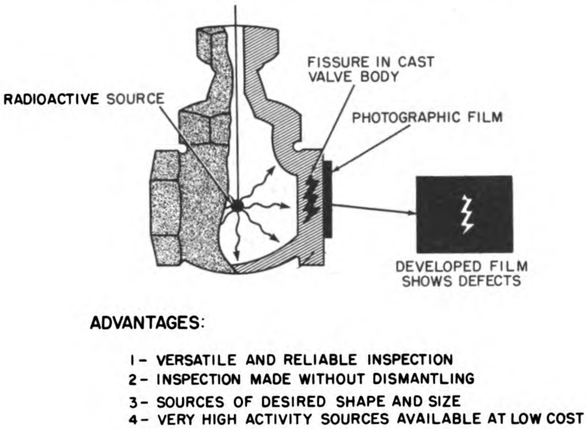


Fig. 8-11. Diagram Outlining the Basic Principles Involved in Radiography Testing. Courtesy of USAEC.

Food Preservation

A great deal of work has been carried out in all parts of the country on the preservation of food by nuclear radiation. It is known

that a sufficiently high level of radiation will destroy the microorganisms which cause food spoilage, but there may be other side-effects which might adversely affect taste and nutritive value. Also, since radioactive materials are expensive, it is necessary to determine the absolute minimum amount of radiation which will produce the desired effects.

According to a report published in a recent issue of Nucleonics magazine, scientists at Brookhaven National Laboratory have succeeded in slowing the spoilage of potatoes and prolonging their storage time by exposing them to nuclear radiation. This work revealed that the radiation inhibited sprouting as well as spoilage, thus indicating a growth-slowing effect in addition to destroying the bacteria which produce spoilage. The scientists suggested that this technique appears to have commercial application, and might be used to prolong the storage of other foods.

Trichinosis is a disease which may be contracted by eating infected pork which is uncooked or improperly prepared. It is caused by small worms in the pork which must be killed before the meat is eaten. Scientists have been attempting to determine if these worms can be killed by nuclear radiation, and if so, how large a dose is required. Preliminary work seems to indicate that extremely large amounts of radiation are necessary, perhaps in the order of 750,000 to 1,000,000 rep. However, 20,000 rep will prevent larvae from maturing to adults, and 12,000 rep will sterilize the females. Such dosages would be far too expensive in the present state of the art, but reduction in the prices of isotopes and fission products may make this method of treating pork feasible.

Work has been under way for some time on the preservation of food by means of a beam of high-speed electrons. The object is to wrap the food first in a sealed plastic package of some kind, and then irradiate the whole package. Tests indicate that such techniques will permit storage of food for long periods of time without refrigeration and without deterioration. Radioactive fission products and isotopes may in the future provide relatively cheap sources of electrons (beta rays) for such purposes. Perhaps refrigerators will become obsolete, except for preparing ice cubes and the like!

Estimating Age of Biological Remains

An extremely interesting application of nuclear science is that of determining approximately how old any dead remains might be. Age is estimated in accordance with the relative percentage of radioactive carbon C^{14}, which is found in the specimen.

The basic assumption underlying this technique is that cosmic rays, which strike the atmosphere, have always been similar in strength to those which we experience at present. These cosmic rays

produce neutrons, which in turn react with nitrogen to produce C^{14}, radioactive carbon.

$$N^{14} + n \rightarrow C^{14} + p$$

This C^{14} is oxidized quickly to produce carbon dioxide, Co_2. Thus, a small but constant percentage of carbon dioxide present in the air contains radioactive carbon. The entire biological world receives its carbon either directly or indirectly from the Co_2 in the atmosphere, so the C^{14} concentration in living materials can be expected to be the same as that in the atmosphere. At the cessation of life, assimilation stops, and a gradual deterioration of the radioactive carbon begins. Since we know that C^{14} has a half-life of about 5,568 years, and that its concentration percentage was originally equal to that of the earth's atmosphere, the relative percentage of carbon which is still radioactive is an index to the age of the remains.

The amount of radioactivity in experiments of this nature is extremely small, sometimes of the order of 4 or 5 disintegrations per minute. Therefore, a great deal of care must be taken to shield the equipment from external radioactivity and cosmic rays, and to remove all traces of elements from the carbon which might be radioactive. One interesting aspect of this problem is that lead, ordinarily thought of as the best shielding material, is more or less radioactive, because it ordinarily occurs in association with uranium and thorium ores. Of the relatively cheap and heavy materials which are suitable for shielding, iron seems to be the most free from radioactive contamination. In spite of the experimental difficulties involved, measurements have been made on a number of samples with significant results.

Leak Detection

An ever-present problem in the maintenance of industrial heat transfer and other equipment is the detection and location of leaks. Many techniques have been used to detect such leaks, some good and some not so good. If the leak occurs in equipment which is entirely enclosed, the problem of detection can become very difficult.

The sketch in Fig. 8-12 shows a practical application of the radioisotope method for determining leaks, presented by the Atomic Energy Commission. This particular case involved a ranch-type residential dwelling with copper tubes buried in the concrete floor to provide radiant heating. A leak or break in the tubing was suspected, but attempts to locate it by conventional means failed.

A slight amount of radioactive iodine 131 (one to two millicuries) was added to the water in the heating system, and the floor systematically explored with a Geiger counter. The location of the leak was determined by the large increase in radioactivity in the area surrounding the leak. It was only necessary to remove a section of floor approximately 6" in diameter to find the break.

Figure 8-13 shows the technique used to explore the floor for an increase in radioactivity. Here a Tracerlab Model SU-5A is being employed to locate a leak in a radiant heating system to which a small amount of radioactive iodine has been added.

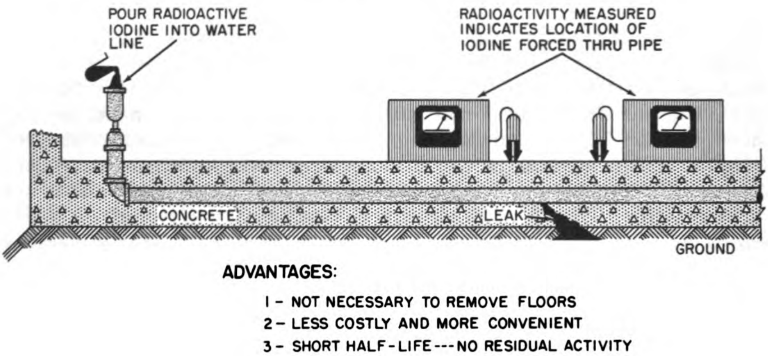


Fig. 8-12. Use of Radioactive Iodine for Detecting Leaks in Water Lines. Courtesy of USAEC.

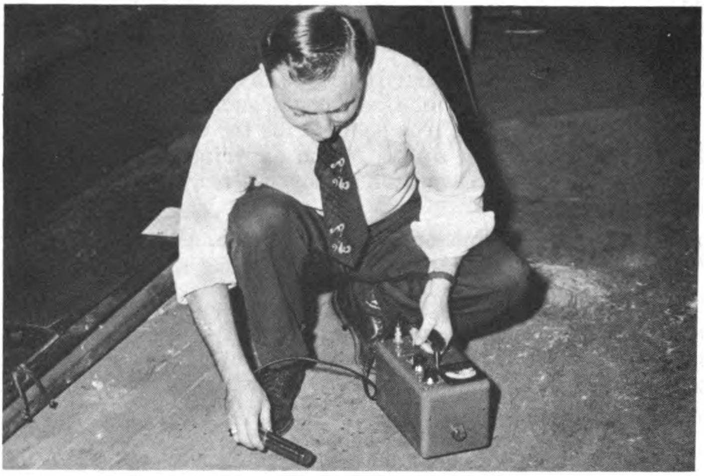


Fig. 8-13. Geiger Counter Being Employed to Check for a Leak in a Radiant Heating System. Iodine 131 has been Added to the Water in the System. Courtesy of Tracerlab, Incorporated.

Oil Flow Tracing

Oil pumps and pipe lines are used to transfer a variety of products from one location to another. When the same pump and pipe line is employed successively for two different products, there is the problem of accurately locating the interface between the two products to avoid excessive mixture.

A technique which has worked out very satisfactorily is shown in Fig. 8-14. A small amount of a radioactive isotope, in this case about a millicurie of oil-soluble antimony 124 (half life, 60 days) is

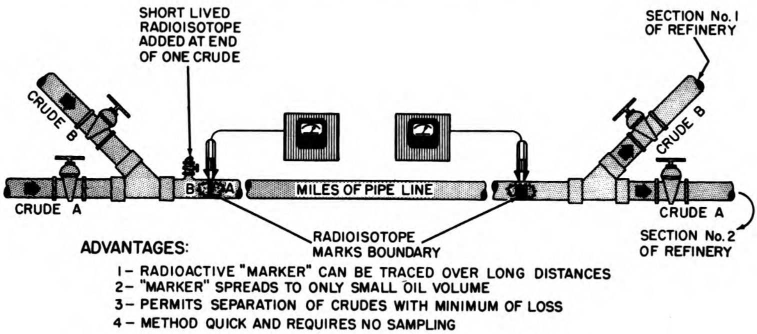


Fig. 8-14. Radioactive Isotopes May Be Used for Tracing Oil Flow in Pipelines. Courtesy of USAEC.

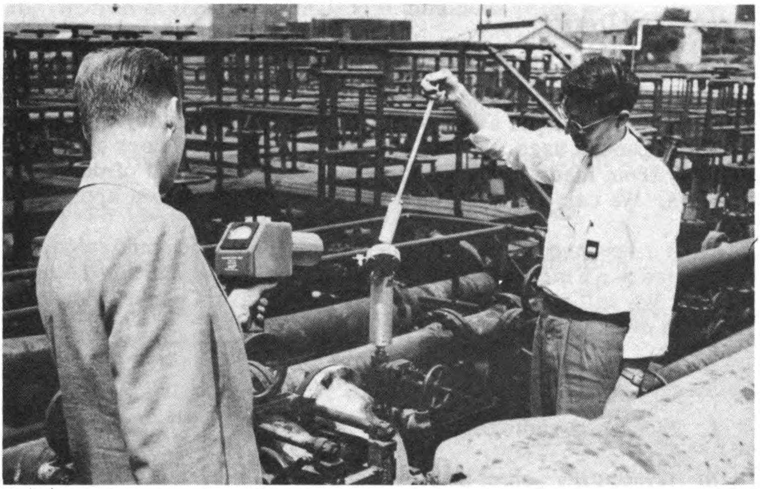


Fig. 8-15. Radiation Survey Meter Being Used to Detect Interface Tagging in Pipelines. Courtesy of Tracerlab, Inc.

added at the interface at the transmitting end, and the interface detected by means of a Geiger counter at the receiving end. Savings realized from this technique in one installation paid for the cost of the measuring equipment in one week. It is even possible to use the radiation from the interface to start and stop pumps by remote control.

The photograph of Fig. 8-15 shows the Tracerlab Model SU-1F survey meter being used for interface tagging on pipe lines. Note that

the worker facing the camera is wearing a film badge dosimeter, a recommended procedure for anyone dealing with radioactivity of any kind.

Static Eliminators

Accumulations of static electricity can be a nuisance or even a hazard in many industrial and medical operations. Properly placed quantities of radioactive material can serve to dissipate such charges gradually, or prevent their formation, before a spark discharge can take place and perhaps ignite inflammable material in the vicinity. The presence of static charges is particularly bothersome in dry atmospheres.

The new vinyl phonograph records are very prone to accumulate a static charge and so attract dust particles, lint, dirt, etc. Some manufacturers now sell a static-elimination brush containing a small quantity of radioactive material such as polonium. Radiation from the polonium discharges the static electricity on the record or prevents it from forming altogether, thus allowing the brush to remove accumulations of dirt and dust.

Isotopes and Tracers

The use of radioactive isotopes in tracer work is in its infancy, and the field of application is almost endless. In spite of the high costs of such isotopes at present, practically every day brings about new or expanded uses. Fields of endeavor where tracers can be useful vary from medicine to farming to industry, and all of the steps in between. We can only touch on a few of the many present applications.

In a recent publication of the Atomic Energy Commission, there was listed a number of isotope allocations considered to be significant. We will present a few of these, to give a general idea of the extreme diversification involved:

1. Thickness gages.

2. Industrial radiography.

3. Irradiating cotton seed and soy bean seed to study gene mutations in an effort to produce new breeding materials for the improvement or development of new varieties.

4. Study of food deterioration.

5. Study of sulfur metabolism in plants and the mechanism of the control of plant rusts by sulfur treatment.

6. Study of effectiveness of electrified sprays.

7. Determine amount of gear wear under various conditions of lubrication.

8. Study of the behaviour of petroleum products in internal combustion engines.

9. Study of flow of heavy petroleum products in pipelines.

10. Investigate nature and location of sulfur deposits in diesel engines.

11. Determine wear in automobile engines and develop lubricants to reduce this wear.

12. Investigate radioactivity bore hole logging techniques for direct measurement of underground formations.

13. Study rate of water vapor transmission through various paper products.

14. Evaluate water displacing properties of rust preventive compounds and fingerprint removing compounds.

15. Investigate the effects of radiation on chemical reactions.

16. Source of ionizing radiation in luminous paint.

17. Locate buried telephone and electric conduits.

18. Study detergency effectiveness in removing contaminated soil.

19. Study the distribution of water in precooked rice.

20. Study the movement of preservatives in wood.

21. Study metabolism of molds in relation to penicillin production.

22. Develop method for quantitative determination of silver in developed image.

23. Measure tire tread wear as a function of vehicle velocity, road surface, road temperature, etc.

24. Study the wear of cutting tools.

25. Determine mixing efficiency of food mixers.

An interesting application recently announced by Nuclear-Chicago is the use of radioactive dirt to test the efficiency of various laundering processes. Radioactivity is in the form of C^{14} – tagged protein, carbon black, or fat applied to cloth swatches. Measurement of radioactivity after washing compared with the same measurement made before washing shows the extent of soil removal.

In the medical field, radioactive iodine is used in thyroid studies and treatment, and other isotopes have found extensive applications in medical diagnosis and therapy. Much work has been

done in the field of agriculture, in determining the effects of fertilizers, tracing plant growth, etc. Practically all tracer work requires specialized instruments for the detection and measurement of radiation involved.

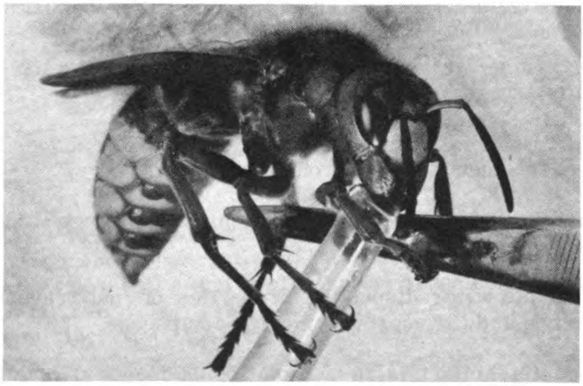


Fig. 8-16. Hornet Eating Honey Which Contains Radioactive Barium. Courtesy of Brookhaven National Laboratory.

Biologists at Brookhaven National Laboratory have used isotopes to determine the effects of minute amounts of barium, copper, iron, calcium, and other minerals on insect life, as clues to a better understanding of the role such minerals play in life processes. In Fig. 8-16, a hornet is shown eating honey which contains radioactive barium. Later, various sections of the hornet tissue will be placed against photographic film, which is darkened by radiation from any radiobarium absorbed by the tissue.

Nuclear Reactors

Most of the nuclear reactors in use at present have been built by the Atomic Energy Commission, and are under direct control of the Commission. Such a reactor is the one at Brookhaven National Laboratory, the west face of which is shown in Fig. 8-17. Here equipment has been hauled out of the reactor into the oblong lead and steel "cave" (center) for safe handling following completion of an experiment. The reactor is of course shut off during insertion and removal operations. A health physicist (center) uses a survey meter to determine safe working conditions.

The Materials Testing reactor at Idaho Falls is operated primarily for the purpose of testing the effects of large densities of both fast and thermal neutrons on various materials. To provide such a large density, the uranium 235 fissions at a high rate, releasing a great deal of power. Heat equivalent to 30,000 kw is produced within a space about the size of two large suitcases. A flow of over 300

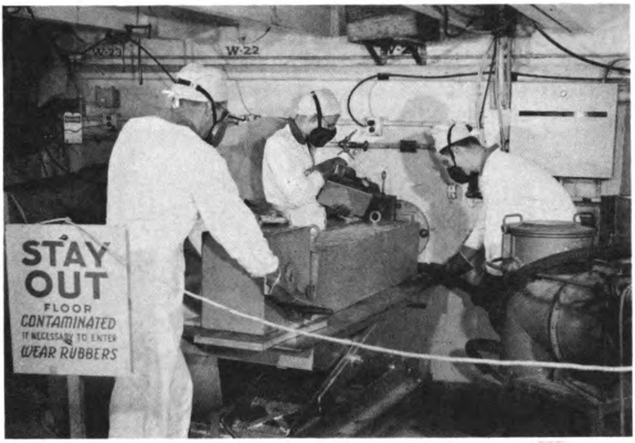


Fig. 8-17. Removing Experimental Equipment From the West Face of the Brookhaven Nuclear Reactor. Courtesy of Brookhaven National Laboratory.

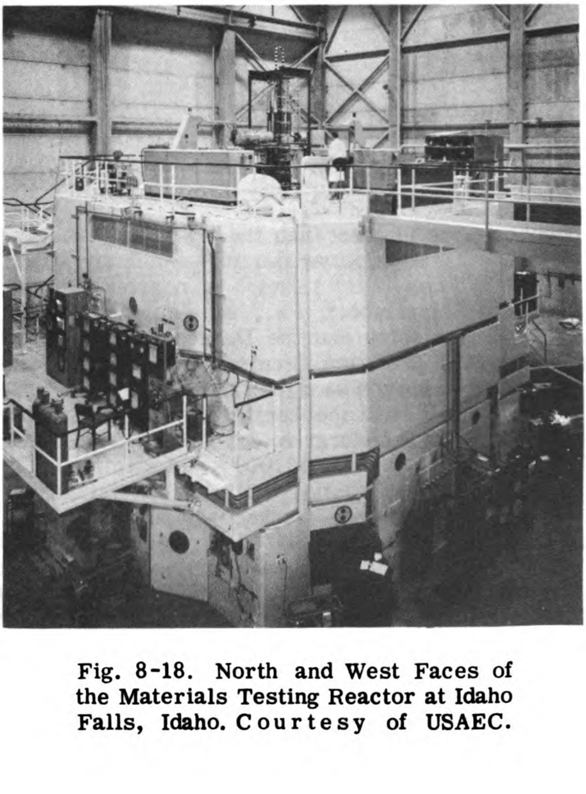


Fig. 8-18. North and West Faces of the Materials Testing Reactor at Idaho Falls, Idaho. Courtesy of USAEC.

gallons of water per second is needed to remove the heat. Concrete walls 9 feet thick surround the reactor, reducing the intensity of radiation to a point where personnel can safely work outside the walls

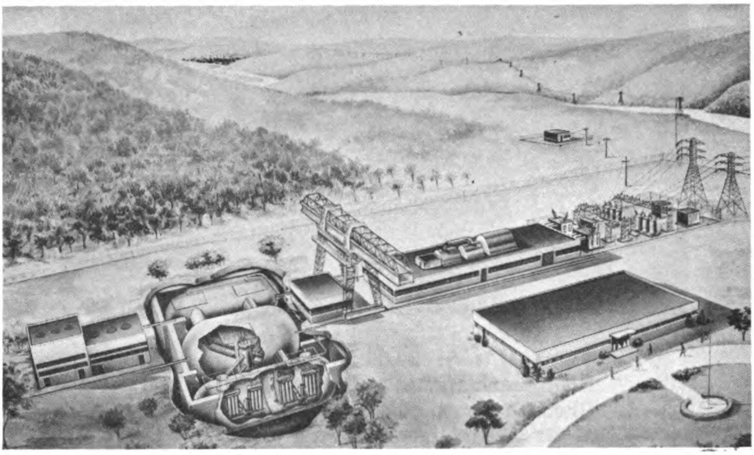


Fig. 8-19. Preliminary Artist's Sketch of Proposed Central Station Atomic Power Plant to be Built at Shippingport, Pa. Courtesy of Westinghouse Electric Corp.

even when the reactor is operating at full power. Figure 8-18 shows the north and west faces of the reactor, with the bridge leading from the reactor top to the control room.

Of perhaps more interest than the so-called "research" reactors are the central station power reactors which are being planned. Shown in Fig. 8-19 is an artist's sketch of a proposed atomic power plant to be built at Shippingport, Pa., as a joint project of the U. S. Atomic Energy Commission and the Duquesne Light Company, with Westinghouse Electric Company developing and building the reactor portion of the plant under contract with the AEC. The atomic reactor which provides the heat, and the heat exchangers which generate the steam, will be located underground. This pioneer nuclear power plant will produce a minimum of 60,000 kw of electricity.

At least one company is prepared to build comparatively low cost research reactors for industry, schools, or other desired applications. The Babcock and Wilcox Company has placed on the market two such reactors for use in training badly needed personnel for the nuclear power industry as well as for conducting basic nuclear research and development. These designs are modified versions of the so-called "water boiler" and "swimming pool" reactors developed by AEC.

A cross-sectional view of the "water boiler" reactor is given in Fig. 8-20. It is a semi-homogeneous unit comprising a solution of enriched (U^{235} added) uranium sulfate in water as fuel and moderator, and a separate cooling system. Its rated power is from 200 to 400 kw, but it can be operated at any power below this level.

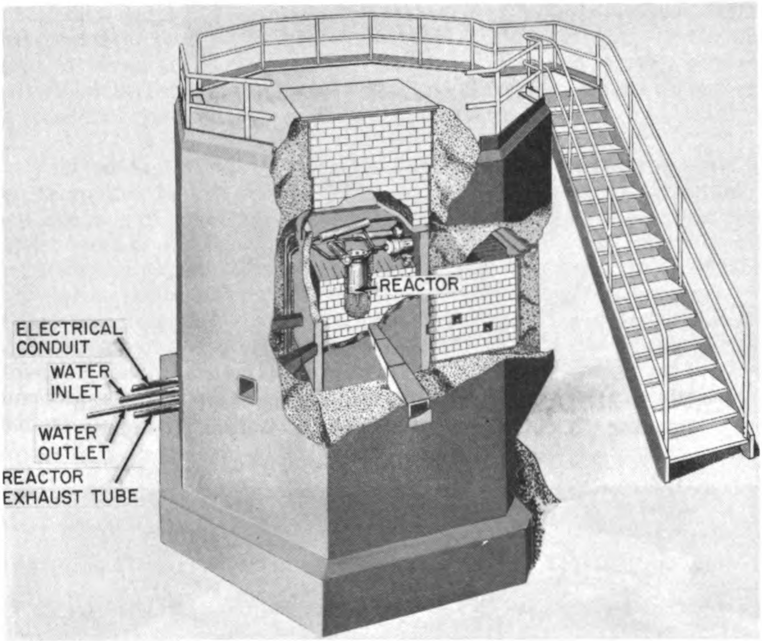


Fig. 8-20. Cross-Section of "Water Boiler" Research Reactor. Courtesy of Babcock & Wilcox Company.

The "swimming pool" reactor, Fig. 8-21, features a high degree of flexibility. It utilizes a heterogeneous core, with a minimum critical mass of about 2.75 kilograms. Maximum power is about 1000 kw. The pool is about 10 feet wide by 20 feet long by 25 feet deep.

What is said to be the first industry-owned and operated nuclear research reactor is being planned by American Machine & Foundry. It will be of the swimming pool type, and will be made available to private industry for research investigations into such fields as sterilization and pasteurization of foods, radiation, chemistry, biochemistry and biology, radioisotope production, medicine, physics, and reactor technology.

An artist's "cutaway" view of the planned reactor is shown in Fig. 8-22. It utilizes unitized design to provide flexibility in operation.

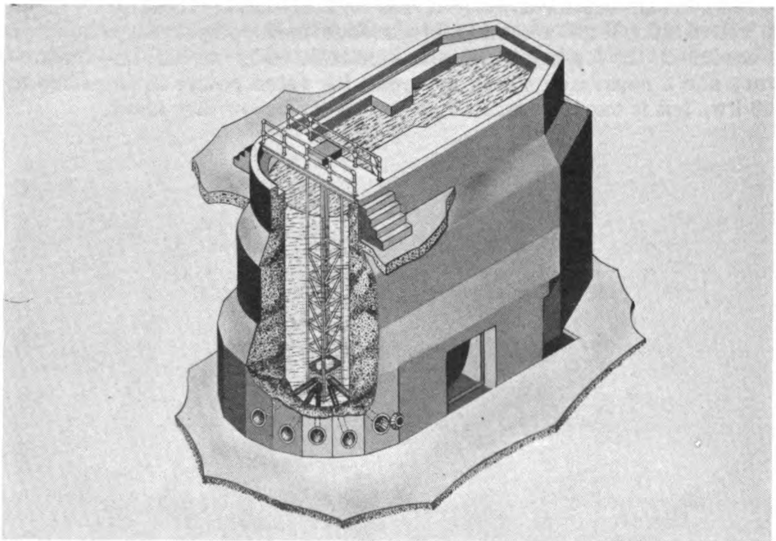


Fig. 8-21. Cross-Section of "Swimming Pool" Research Reactor. Courtesy of Babcock & Wilcox Company.

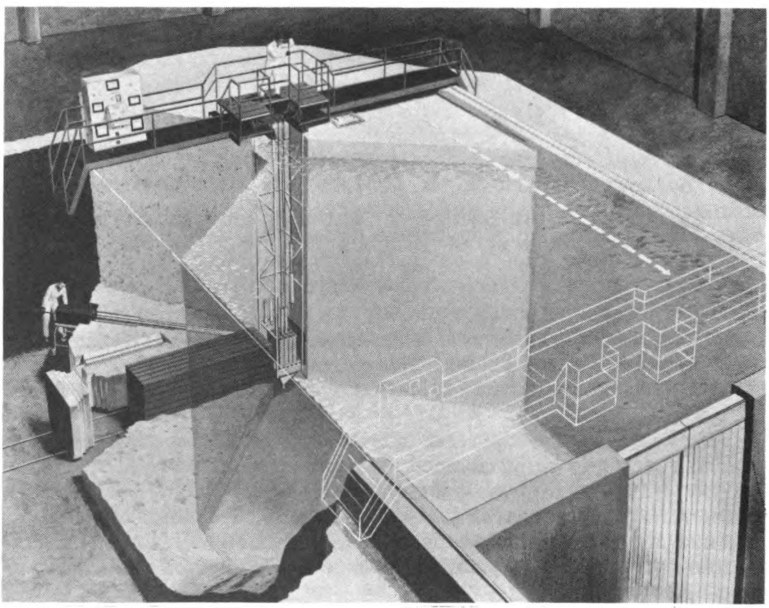


Fig. 8-22. Artist's Sketch of AMF Nuclear Research Reactor. Courtesy of American Machine & Foundry Co.

Future

At the present time, generation of power from atomic energy involves utilizing the heat generated by the nuclear reactor to produce power in some manner. It is interesting to speculate on the possibility of the direct conversion of the energy of nuclear reactions to electrical energy without the necessity of passing through any intermediate steps. Many people are undoubtedly seriously considering this problem, but no solution has been suggested as yet. The problems involved are terrific, and it may be that a satisfactory solution will never be found. However, we would be foolish indeed if we were to state that the problems are insurmountable.

Some hints have been given in this chapter as to the possible future applications of nuclear science. The horizons are unlimited — new avenues of research are continually opening up. The major problem is and probably will continue to be the protection of personnel from excessive radiation. Perhaps someone will discover or develop a shielding material which is much more efficient than lead, but from theoretical considerations, such possibilities rank along with the possibilities of discovering an "anti-gravity" shielding material! However, such speculation must not lead us astray from the tremendous number of presently-known and forseeable applications of nuclear science.

CHAPTER 9

Civil Defense

Most of the potential target areas for atomic attack — industrial urban areas and areas surrounding military establishments — have been theoretically mapped out to show the relative destruction which could be expected if an atomic bomb were exploded at any of a number of points in the area. This has been based on the results of radiation measurements taken during the many experimental detonations of A-bombs. The public has been informed through newspaper and periodical stories.

Potential dangers from the A-bomb are related to the proximity of its detonation. Everything and everyone close to it will be subject to complete destruction. As the distance increases, the relative danger decreases.

Authorities concerned with planning for civil defense in case of an atomic attack were handed a new headache recently when the results of the hydrogen bomb tested at Bikini in March, 1954 were made known. This test revealed a new hazard not previously considered serious — that of radioactive fall-out.

The term radioactive fall-out has been bandied about a great deal, so it might be well to explain just what it means. When an atomic bomb explodes, a tremendous amount of radioactivity is released instantaneously. In addition, quantities of fission products are formed — products resulting from the disintegration of the uranium or plutonium atoms. Many of these products are highly radioactive. Their half-life varies widely, but is relatively short for most, so the amount of radioactivity falls off fairly rapidly.

In an atom bomb burst, these products are dissipated very widely in the atmosphere, and are not a serious problem. With a hydrogen bomb burst, the radioactive fission products are much more numerous. Also, the fireball produced with such a burst is so large and so intense that huge quantities of dirt, dust, and sand are sucked into the vortex resulting from the blast. These particles become coated with the radioactive fission products of the bomb. Such particles, now highly radioactive, are first carried far up into the air,

then start to drift down and fall on the earth below. The heavier particles fall quite rapidly and so land fairly close to the original blast. The lighter particles, however, are carried by the prevailing winds, and may travel for a hundred or more miles before falling. It is these radioactive particles of dirt, dust, sand, and fission products that constitute the radioactive fall-out from a hydrogen bomb burst.

The civil defense problem arises from the fact that this fall-out can be deadly for as far as 140 miles from the original burst, and can be serious for at least another 50 miles. In fact, unless proper protection were available, every human being could be killed in a strip about 140 miles long by 40 miles wide, and many more deaths and injuries would result in the area extending another 50 or more miles.

There are a number of factors with which civil defense authorities have to cope, but such matters as evacuation, medical care, etc., are beyond the scope of this book. We will be concerned primarily with those factors involving the detection and measurement of radiation during and after an atomic attack.

First it might be well to review briefly some of the material in Chapter 3, outlining the maximum permissible exposures under various conditions. It has been pretty well established that an exposure of 0.3 r per week should not be exceeded normally; however, under emergency conditions, a person could accept an exposure to the whole body of 25 r in a single day.

An acute dosage of 50 r ordinarily will not affect efficiency of a group of people as a working unit. An acute dosage of 100 r will probably produce occasional nausea in some individuals, but not to the extent of rendering personnel ineffective as groups. If the acute exposure reaches 100 r or more, the individuals involved should be relieved from duty immediately. Groups receiving exposure greater than this will rapidly become ineffective. For acute doses up to 150 r, mortality will be very low, and eventual recovery may be expected. Greater exposures will result in greatly increased sickness and mortality rates.

The Federal Civil Defense Administration has established the following "rule of thumb" guide regarding repeated exposures. An exposure of 25 r per day at weekly or longer intervals for a total of eight exposures (200 r) may be experienced without serious loss of efficiency due either to illness or significant general deterioration in health and ability. Before each probable re-exposure, the degree of radiation damage already produced and that to be expected should be evaluated. Although not strictly true, to be on the safe side repeated daily exposures should be considered to be directly additive.

Total radiation exposure may be determined by means of a suitable personal dosimeter, or by means of a survey meter of some kind which indicates intensity. In the latter case, the intensity must

be multiplied by the time of exposure to determine the total dose. For example, in an area where the general radiation level is measured as 25 r/hr, an individual would receive a dose of 25 r for every hour of exposure. If the level is 50 mr/hr, an exposure of 20 hours would be required to produce a total dose of 1 r.

Many different types of dosimeters were discussed in Chapter 7, and this discussion need not be repeated here, other than to indicate some advantages and disadvantages of a few. For example, in the film type dosimeter the film must be removed, developed, and compared to some standard before an accurate indication of exposure can be obtained. Self-developing, self-reading film badges overcome this disadvantage somewhat, but there is still a certain amount of time lag involved. On the other hand, the self-reading electrostatic type can be read as desired, but is available only in relatively low ranges of total exposure, and requires auxiliary equipment for charging. Chemical dosimeters show considerable promise, but no completely satisfactory instrument has yet been developed. Phosphate glass units require auxiliary equipment for reading, and this equipment might not be available or might be inoperative in time of an emergency. It is desirable that a personal dosimeter be capable of indicating a dose of 50 to 600 r fairly accurately, and that the accuracy be retained under conditions where a large amount of radiation is received in a very short period of time, as in a bomb explosion.

The Civil Defense Administration differentiates between the personal dosimeter, and the organizational dosimeter, worn by civil defense workers in contaminated areas. The latter is more accurate and has a lower range than the former, and in general would probably be some variation of the electrostatic type.

It is highly probable that radioactive fall-out will be a major problem if we are ever subjected to an atomic attack. As mentioned before, effects of this fall-out could be lethal over a wide area without adequate protection. It would be necessary then, to survey the area in question to determine the general level of radioactivity, and so determine the length of time that an individual can safely stay in the area. Instruments which are suitable for this purpose were described in some detail in Chapters 4 and 5. It should be emphasized that only those instruments which have been calibrated to indicate radiation intensity directly should be relied on for such surveys, and then only if there is good reason to believe that the calibrations are fairly accurate, and if the readings are taken and interpreted by a person trained in their use.

Fig. 9-1 shows an instrument being employed to survey snow which was suspected of being radioactive. Although this particular survey was not made as a result of an atomic attack, nevertheless, the same procedures and techniques can be applied.

If an individual has been subjected to radioactive fall-out without adequate protection, any contaminated clothing should be removed

as soon as possible, and the person's skin and hair scrubbed to remove all traces of radioactive dust or dirt. This will prevent further needless exposure to radiation. Most any kind of protection will be helpful during fall-out, as long as radioactive dust does not actually fall on the individual. A slit trench with a cover of some kind over it

Fig. 9-1. A Victoreen Scintillation Counter Being Used to Check the Radioactivity of Freshly Fallen Snow Following an Atom Bomb Test. Courtesy of Victoreen Instrument Co.

will cut down tremendously on total exposure, as will a building of any kind. An important point to remember is to keep under cover until some assurance has been obtained that the intensity of radiation in the area has fallen off to a safe level. Even in areas of very severe fall-out, injuries can be held to a bare minimum if individuals will keep themselves protected for a couple of days.

Another very serious problem that would be encountered in case of an atomic attack and radioactive fall-out is that of contamination of food and drinking water. The problem arises not only from the standpoint of condemning materials containing excessive radioactivity, but also avoiding the unnecessary condemnation of materials which are not dangerous, and thus denying their use during the emergency.

Here again the Federal Civil Defense Administration has set up standards to serve as a guide. For example, during a 10-day

period, concentration of radioactivity in food or drinking water should not exceed 0.09 $\mu c/cc$, or 3000 dps/cc, where the primary radiation products are beta and gamma rays. For a 30-day period, the concentration should not exceed 0.03 $\mu c/cc$, or 1000 dps/cc.

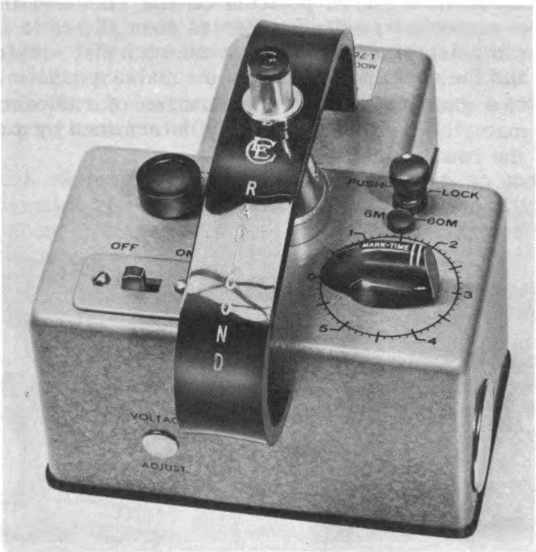


Fig. 9-2. Landsverk Radicond Model L-76 Which Can Be Used to Check the Radioactivity of Food or Liquids. Courtesy of Landsverk Electrometer Co.

Since the RBE of alpha rays is about 20, meaning that alpha rays are about 20 times as destructive to human tissue as gamma rays, it would be expected that only 1/20th as much alpha activity would be permitted. This is roughly true — for a 10-day period, the maximum acceptable concentration of alpha activity is 0.005 $\mu c/cc$, or 180 dps/cc, and for a 30-day period, 0.0017 $\mu c/cc$, or 60 dps/cc.

The values given above are not peacetime permissible limits for either long- or short-term consumption. Values for beta and gamma activity are applicable only during the first month following an atomic bomb burst. Radioactivity remaining after a month is due to the more hazardous longer-lived fission products and a more complete study is necessary. However, the values for alpha activity are not limited to the month following an atomic explosion but may be applied to any 10- or 30-day period.

Many standard commercially available instruments are sufficiently sensitive to detect the emergency beta and gamma levels. A sensitivity of 0-20 mr/hr is satisfactory, provided that the instrument is capable of detecting beta rays. Very few instruments can

detect alpha rays because of the very short range of such rays and the thin windows required to permit their penetration.

To satisfactorily check food or water with a Geiger counter, a standard source is essential. The Geiger probe, with the beta shield open, is placed in a known position on the standard and a reading taken. The suspected food or water is then placed to a depth of at least 2 mm in a container of the same size as that employed for the standard, and the container placed in the same position as that occupied by the standard. The concentration of radioactivity in the suspected material can then be roughly determined by a direct comparison of the two readings.

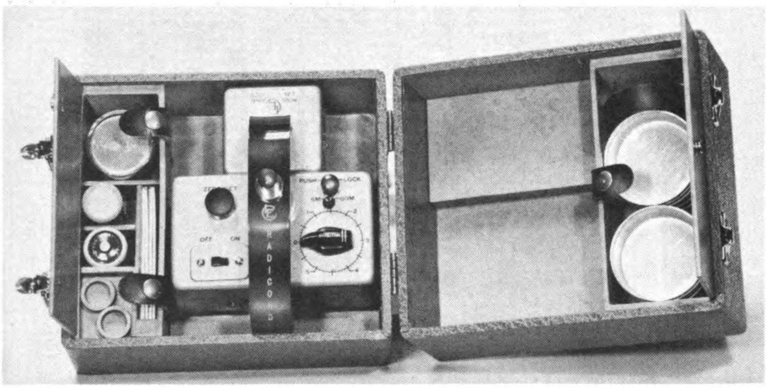


Fig. 9-3. The Landsverk Radicond in its Carrying Case Complete with Auxiliary Equipment Including Planchets and Batteries. Courtesy of Landsverk Electrometer Company.

The technique described above has certain important disadvantages; one being the failure to provide for the wide discrepancy that exists between the response to various ages of fission products and their potential hazard when taken internally.

An instrument called the Radicond has been designed by the Landsverk Electrometer Company to overcome the disadvantages of the technique described in the foregoing, and to provide a convenient and accurate means of rapidly determining the radioactive content of food and water. This instrument, known as the Model L-76, is shown in Fig. 9-2.

The Radicond (Radiation Contamination Detector) has a built-in double range mechanical timer linked to a quartz fiber voltmeter, so that the reading is taken directly from the microscope scale of the voltmeter at the end of the timer interval without need for calculation or interpretation. Timer settings may be varied with the time after the bomb explosion according to a graph or table. The

settings can be adjusted so that the instrument gives the same readings for the same number of disintegrations per cc per second over the entire 10-day or 30-day emergency period.

The voltmeter is initially set to zero by an internal battery supply and "zero set" potentiometer. A special aluminum dish is filled with the sample being tested and slid in place under the ionization chamber. When the timer is set, operation begins and at the end of the timing period the voltmeter indicates total exposure. Figure 9-3 shows the instrument and all accessories mounted in a suitable carrying case.

Although sketchy, this description will give an indication of the basic operation of the Radicond. Its range of sensitivity is tremendous — about 1,000,000 to 1 — making it an extremely useful device.

This rough outline is intended to give an indication of some of the factors involved in the detection and measurement of radiation in case of an atomic attack. Further details are available in a series of bulletins put out by the Federal Civil Defense Administration and available from the U. S. Government Printing Office, Washington 25, D. C

CHAPTER 10

Prospecting

Perhaps the most glamorous aspect of the detection and measurement of atomic radiation is that of prospecting for radioactive ores, such as uranium and thorium. This activity has become a pastime of thousands of vacationers as well as a full-time vocation for many individuals. To some, these activities have proved highly profitable as in the much-publicized case of Vernon Pick; to others, such activities have resulted primarily in a plentiful supply of fresh air and exercise.

Uranium (and to a lesser extent thorium) prospecting has been encouraged by the Atomic Energy Commission in many ways. Cash bonuses are given for larger "strikes", and purchase of uranium ore above a certain percentage yield is guaranteed at a price which makes uranium mining very profitable. Anyone contemplating serious prospecting should become familiar with the various incentives which have been provided. Such information is included in Government publications which will be discussed later in this chapter.

It is possible to prospect for uranium without a Geiger counter or other radiation-detecting device. The various ores of uranium have certain characteristic colors and textures which permit identification by means of visual examination, especially after a little experience has been gained by carefully examining known ores or color photographs of such ores. However, we are primarily concerned with atomic radiation in this book, and so will discuss only those types of prospecting in which equipment of some kind is used for detecting radiation, and determining, at least roughly, the intensity of such radiation. See Fig. 10-1.

Anyone seriously concerned with prospecting even on a small scale, should purchase and read two Government publications: "Prospecting for Uranium" (55¢) and "Prospecting With a Counter" (30¢). Both of these are published by the Atomic Energy Commission, and are available from the Superintendent of Documents, Government Printing Office, Washington 25, D. C. These publications provide a wealth of information on prospecting, and outline the bonuses and incentive payments available to those discovering uranium ores. The

book "Prospecting for Uranium" contains several color plates to assist in visually identifying various ores, and also includes an extensive appendix which provides a great deal of useful information on such matters as AEC licensing regulations, mining claims on the public domain, and the like.

Before discussing prospecting and the equipment used, it is advisable to review briefly some of the characteristics of uranium and uranium ores, and of the radiation given off by such ores.

Fig. 10-1. The Fisher "M-Scope", a Small, Inexpensive Counter, Being Used to Check the Radioactivity of a Piece of Rock. Courtesy of Fisher Research Laboratory, Incorporated.

All presently available detection equipment operates by detecting gamma radiation, since any alpha or beta rays have such a short range that their primary effects can be ignored. Uranium itself does not give off gamma rays — when the uranium atom disintegrates, some of the radioactive products give off gamma rays, and it is this secondary gamma radiation that is detected. We have learned that gamma rays have considerable penetrating power, but their range is by no means unlimited, and this single factor is perhaps the most important point to remember in prospecting.

A layer of about two feet of rock or five feet of overburden, such as soil, is sufficient to block all gamma rays given off by any known radioactive substances. Therefore, with certain limitations, surface prospecting is useful only in detecting surface outcropping of ore. Extensive prospecting for underground ores then requires drilling or digging operations which can become very expensive, unless

there is reasonable assurance that uranium will be discovered. The exceptions mentioned above are brought about by the fact that one of the byproducts of the disintegration of uranium is a radioactive gas, **radon**, which may diffuse upwards through overburden and so give an indication of excessive radiation in the area.

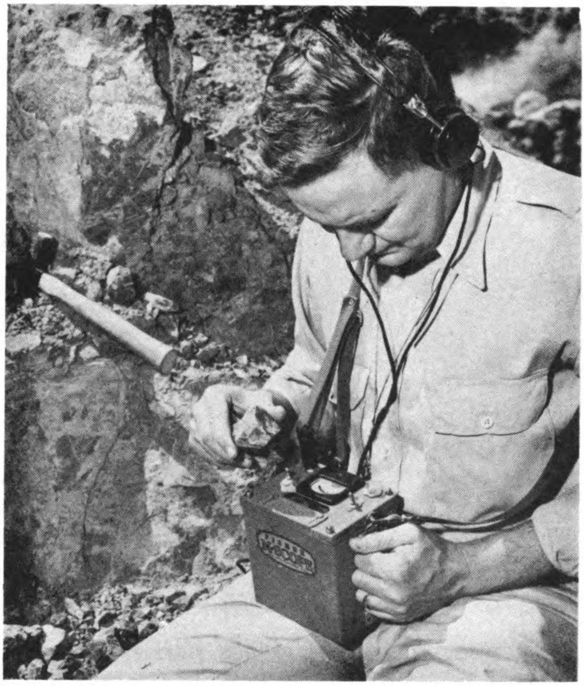


Fig. 10-2. A More Elaborate Counter Which Provides Both a Meter and Headphone Indication. Courtesy of Fisher Research Laboratory, Inc.

Another important point to consider is that the background count may vary considerably in a given area, and this background count should be carefully determined. It is then safe to say that further investigation is warranted if the actual count at a given location exceeds the background count by a factor of 2 to 1 or more.

Aerial prospecting has been used extensively in the last three or four years. However, it is quite expensive, and different equipment and techniques are employed than in ground prospecting. For these reasons, we will discuss the two separately, with the major emphases on ground prospecting.

Ground Prospecting

Geiger counters are used most extensively for ground prospecting, although lately scintillation counter equipment has become

available for hand carrying or for prospecting from a jeep or other motorized vehicle. As discussed in previous chapters, scintillation equipment is more expensive and bulky than Geiger units, and so is not as desirable for the casual prospector.

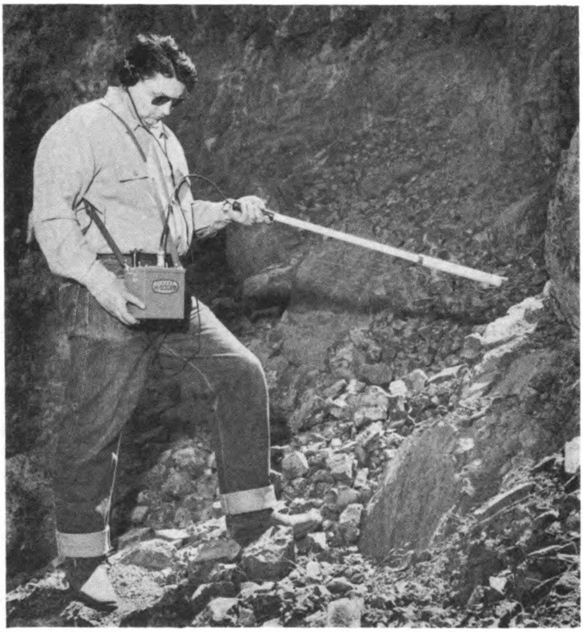


Fig. 10-3. Placing the Geiger Tube at the End of a Long Probe Assists in Checking Crevasses and Other Normally Inaccessible Areas. Courtesy of Fisher Research Laboratory, Incorporated.

Geiger counters suitable for prospecting vary tremendously in price and complexity. See Figs. 10-2 and 10-3. If one is content to count clicks in headphones, or flashes of a neon light, a unit can be obtained quite reasonably — recent prices have been quoted as low as $29.95, and home-built units or kits can perhaps be built for even less expense. If one wants a meter which reads counts per minute or radiation intensity directly, equipment becomes more expensive and more complicated. If all three features are desired, still more cost and complexity are involved. With patience and perseverance, the simplest units can be as effective in discovering radioactive ores as the more expensive models.

Some system should be set up when surveying a given area, in order to avoid covering portions of the area twice and to make certain that all portions are covered. One way of accomplishing this is to mark the area off in a sort of grid network, and then take a reading at each grid intersection. If the grids are sufficiently close together,

this assures uniform coverage and will spot any areas of excessive radiation. The average background count should be determined for the whole area being surveyed, and as mentioned before, counts of twice background should be investigated further.

Fig. 10-4. The Goldak "Colorado" Which Can Be Held in the Hand or Worn Suspended by a Strap Over the Shoulder. Courtesy of the Goldak Company.

Gamma rays have quite a large range in air, so it is not necessary to place the counter against the rock being examined to determine if radioactivity is present. Carrying the counter in the hand or strapping it on the person in some manner are satisfactory techniques which can be employed. See Figs. 10-4 and 10-5.

There are a great many factors involved in determining the richness of a strike, or even in determining if a strike has been made. Some of these factors include radioactive equilibrium of the ores involved, the "mass" effect, direction of prevailing winds, proximity of uranium mining operations, atomic bomb tests, and others which are beyond the scope of this book. These, and many other factors, are discussed in AEC publications mentioned at the beginning of this chapter.

Once an area of excessive radiation has been discovered, an idea of the amount of uranium in the rock in the area can be obtained by comparing a sample of the ore with a sample of ore of known concentration. While not conclusive, such a comparison can give an idea as to whether further investigation is warranted. See Fig. 10-6.

Such a comparison can be made with the simplest counter. Ores of known concentrations can be purchased from various sources. The

best procedure is to grind up a quantity of the known material and place it in a dish of some kind. An identical quantity of the unknown ore is ground up and placed in an identical container. The Geiger counter is placed in position over the known ore, and the counts per minute determined. The counter is then placed in a similar position over the unknown ore, which must be located some distance from the

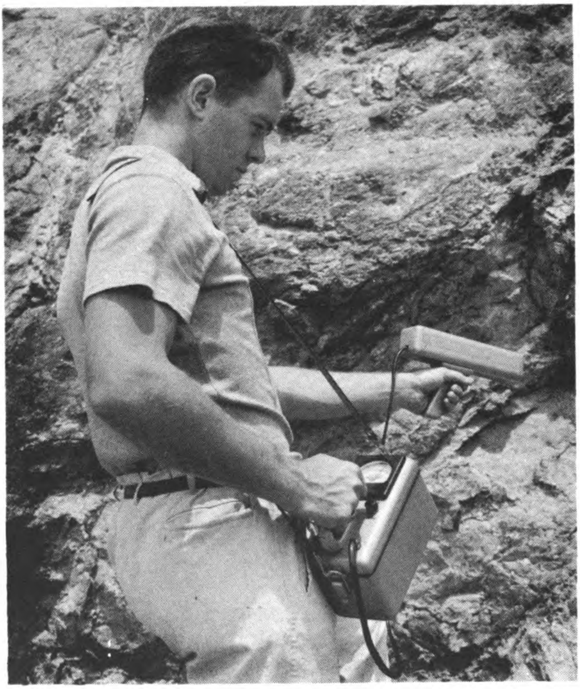


Fig. 10-5. The Goldak "Scintascope", a Scintillation Counter Useful for Ground Prospecting. Courtesy of the Goldak Co.

first sample, and the counts per minute again determined. If the counts are widely different under the two conditions, a known sample of different concentration is tested. This procedure is continued until a known sample is found giving approximately the same count as the unknown sample. The uranium concentration in the two samples is then approximately the same. However, it is always best to have a chemical assay made before anything further is done, especially if a wide variety of known samples is not available.

In some instances, the concentration may be such that the clicks are too rapid to be easily counted. In this case, the Geiger counter is moved away from the sample until a rate is established which is slow enough for counting. When comparing samples, it is extremely important that the distance between sample and counter is identical

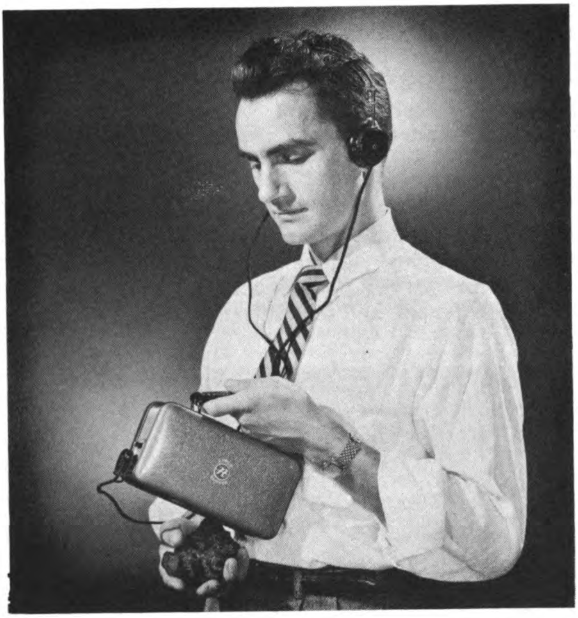


Fig. 10-6. Nuclear-Chicago "Super Sniffer" in Operation. Courtesy of Nuclear Instrument & Chemical Corp.

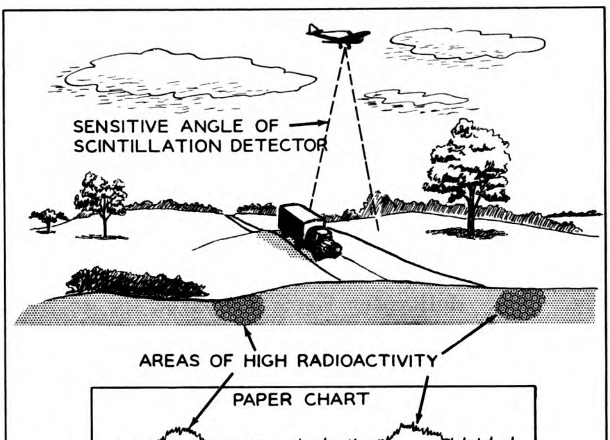


Fig. 10-7. Diagram Showing the Basic Operating Principles of Aerial Surveying. Courtesy of Nuclear Instrument & Chemical Corporation.

in each case, that the samples are prepared in the same way, that identical quantities are present, and that the same size and type of container is used for each sample. It is possible to compare chunks of ore of approximately the same size and shape, but such a comparison is not as reliable as the technique outlined previously.

Aerial Prospecting

The heading for this portion of Chapter 10 should perhaps be called "Aerial Surveying", since a great deal of the present activity in this field is for survey purposes rather than actual prospecting. However, the equipment and techniques are similar. See Fig. 10-7.

Fig. 10-8. Helicopter Being Prepared for an Aerial Survey with a Scintillation Counter. The Vertical Tube in the Doorway of the Plane Contains the Scintillometer Probe. Courtesy of The Radiac Company, Inc.

Scintillation counters are used almost exclusively in aerial surveying, because of the greater sensitivity. For still higher sensitivity, extra large detecting crystals may be employed. In one commerical unit designed specifically for prospecting, a block of special "Plastifluor" material seven inches in diameter is used.

In conducting aerial surveys, the equipment is usually provided with a recorder to make a continuous recording of radiation intensity.

The plane or helicopter may also carry a recording altimeter to provide a continuous record of altitude, since the radiation intensity depends on altitude as well as other factors. See Fig. 10-8.

Grid flying is usually employed in making surveys in fairly level country. A Canadian concern found that for detailed surveys, a 1/4-mile grid appeared to be satisfactory, while a 1-mile grid sufficed for simple reconnaissance. Equipment employed in this type of surveying measured the radioactivity level from a ground path approximately 600 feet wide when the plane was flying at about 550 feet. The same Canadian company found that the optimum height for a plane was about 550 feet — high enough for safe flying, but not too

Fig. 10-9. Airborne Scintillometer in Operation. The Scintillometer Probe is Suspended Beneath the Helicopter. Courtesy of The Radiac Company, Inc.

high to mask radiation from ore deposits. All measurements were corrected to a 550-foot level for uniformity. Above 700 feet, little change in intensity could be detected when flying over known ore deposits. See Fig. 10-9.

The technique most commonly employed is to determine areas in which radiation is significantly above normal, and then to conduct

detailed surveys in these areas on foot with either a scintillation or Geiger counter.

In extremely rough or mountainous country, a technique called "rim flying" may be employed. A helicopter is far superior to a light plane for this purpose, but is also much more expensive to use. The technique consists of following the rim of a canyon, regardless of the directions in which the canyon turns, and keeping the distance between the rim and the plane as nearly constant as possible. Outcroppings of ore can be readily located in this manner.

Aerial surveying for radioactivity has been employed with some success in determining the approximate location of oil fields. There

Fig. 10-10. Prospector Probes for Radioactive Ore with a Curtiss-Wright Radiatector. Courtesy of Curtiss-Wright Corporation.

appears to be a sort of aura of above-normal radioactivity at the boundary of the field, and a subnormal amount of radioactivity directly over the field. By conducting a survey using grid techniques, areas for likely drilling can be outlined. This cannot be called a precision technique as yet, or a sure method of locating oil fields, but has proven valuable when combined with all other available information.

Extensive aerial surveys have been carried out in the United States and other countries as well, under the sponsorship of the Atomic Energy Commission. Several companies have been established which specialize in this type of work, and a number of oil companies have

purchased planes and equipment for conducting their own aerial surveys in areas which appear to show prospects of having oil fields. Because of the expense involved, very few individuals are able to indulge in aerial surveying or prospecting, and it is expected that the individual prospector will have to rely on hand-carried equipment. See Fig. 10-10.

Whatever radiation detection equipment is used, and wherever it is being used, there is a tremendous sense of accomplishment which accompanies an increase in indications. The thrill of having "cornered the quarry" is as great as it could ever be in any sport. The fact that you have found something which is of exceptional scientific and material value adds lore to personal satisfaction.

Now that nuclear science is finding more and more everyday applications which will materialize many present day fantasies, the need for more radioactive materials is ever increasing. The radioactive materials required are available somewhere. Detection and measurement methods outlined in this book can be expected to locate many of these treasure stores and allow continued expansion of the fields of application for our better future.

APPENDIX I

Manufacturers' Directory

This listing is intended to be representative only and should by no means considered to be comprehensive. However, this list, together with the Product Directory in Appendix II, will help greatly in locating a manufacturer of specific equipment.

Abbott Laboratories, North Chicago, Ill.

Amperex Electronic Corp., 230 Duffy Ave., Hicksville, N. Y.

Anton Electronic Labs., Inc., 1226-38 Flushing Ave., Brooklyn 37, N. Y.

Atomic Energy of Canada, Ltd., Commercial Products Div., P. O. Box 93, Ottawa, Ontario, Canada

Atomic Instrument Co., 84 Massachusetts Ave., Cambridge 39, Mass.

Atomlab, Inc., 489 Fifth Ave., New York 17, N. Y.

Beckman, Inc., Arnold O.; 1020 Mission St., South Pasadena, Calif.

Beckman Instruments, Inc., 820 Mission St., South Pasadena 183, Calif.

Bendix Aviation Corporation, Cincinnati Division, 203 W. Third St., Cincinnati 2, Ohio

Berkeley Division of Beckman Instruments, Incorporated, 2200 Wright Ave., Richmond, California.

Bio-Rad Laboratories, 800 Delaware St., Berkeley 9, California.

Cambridge Instrument Co., Inc., Grand Central Terminal, New York 17, New York.

Cam-Mac Division, Micro Specialities Co., 1834 University Avenue Berkeley 3, California.

Chatham Electronics Corporation, Livingston, New Jersey.

Consolidated Engineering Corporation, 300 N. Sierra Madre Villa, Pasadena 15, California.

Corning Glass Works, Corning, New York.

Curtiss-Wright Corp., Electronics Div., Carlstadt, New Jersey.

Cyclotron Specialities Co., Moraga 8, California.

Detectolab, Inc., 6544 N. Sheridan Rd., Chicago 26, Illinois.

Detectron Corp., 5420 Vineland Ave., North Hollywood, California.

Electronic Products Co., 111 E. Third St., Mount Vernon, New York.

El-Tronics, Inc., 5th and Noble Sts., Philadelphia 23, Pa.

Fisher Research Laboratory, Inc., 1961 University Lane, Palo Alto, California.

General Electric Co., Apparatus Sales Div., Schenectady 5, California.

Goldak Co., 1544 W. Glenoaks Blvd., Glendale 1, California.

Harshaw Chemical Co., 1945 E. 97th St., Cleveland 6, Ohio

Hoffman Laboratories, Incorporated, Box 2471, Terminal Annex, Los Angeles 54, California.

Isotope Developments Ltd., Finsbury Pavement House, 120 Moorgati, London E. C. 2, England

Jordan Electronic Mfg. Co., Inc., Union Bldg., 119 E. Union St., Pasadena 1, California.

Landsverk Electrometer Co., 550-552 W. Garfield Ave., Glendale 4, California.

Leighton Laboratories, H. W., 26 Herman St., Glen Ridge, N. J.

Linde Air Products Co., A Div. of Union Carbine & Carbon Corp., 30E. 42nd St., New York 17, New York.

Macdonald Co., Inc., W. S., 33 University Rd., Cambridge 38, Mass.

Menlo Research Laboratory, Menlo Park, California.

National Radiac, Inc., 10 Crawford St., Newark 2, N. J.

North American Philips Co., Inc., 750 S. Fulton Ave., Mt. Vernon, New York.

Nuclear Instrument & Chemical Corp., 229 W. Erie St., Chicago 10, Ill.

Nuclear Measurements Corp., 2460 N. Arlington Ave., Indianapolis, Indiana.

Nucleonic Co. of America, 196 DeGraw St., Brooklyn 31, New York.

Pilot Chemicals, Inc., 47 Felton St., Waltham, Mass.

Precision Radiation Instruments, Inc., 2235 S. La Brea Ave., Los Angeles 16, California.

R-C Scientific Instrument Col, 307 Culver Blvd., Playa Del Rey, Calif.

The Radiac Company, Inc., Div. General Nucleonics Corporation, 489 Fifth Ave., New York 17, New York.

Radiation Counter Labs., Inc., 5122 W. Grove St., Skokie, Illinois.

Radiation Instrument Development Lab., 2337 W. 67th St., Chicago 36, Illinois.

Radioactive Products, Inc., 540 W. Congress St., Detroit 26, Mich.

Raytheon Mfg. Co., Waltham 54, Mass.

Sherwin Instrument Co., 2875 Broadway, New York 25, New York.

Stamco Instrument Corp., Springdale, Conn.

Technical Associates, 140 W. Providencia Ave., Burbank, California.

Tracerlab, Inc., 130 High St., Boston 10, Mass.

Victoreen Instrument Co., 5800 Hough Ave., Cleveland 3, Ohio.

Wakefield Industries, Inc., 5108 Grove St., Skokie, Ill.

Welch Allyn, Inc., Skaneatles Falls, N. Y.

Western Radiation Lab., 1107 W. 24th St., Los Angles 7, California.

Wood Counter Laboratory, N., 5491 Blackstone, Chicago 15, Ill.

Young Sound Engineering Co., J., 800 Stockton St., San Francisco, California.

APPENDIX II

Product Directory

Dosimeters

Bendix Avation Corp., Cincinnati Division

Beckman, Inc., Arnold O.

Berkeley Div. of Beckman Instruments, Inc.

Cambridge Instrument Co., Inc.

Chatham Electronics Corp.

Corning Glass Works

Consolidated Engineering Corp.

El-Tronics, Inc.

General Electric Co.

Landsverk Electrometer Co.

North American Philips Co., Inc.

Nuclear Instrument & Chemical Corp.

R-C Scientific Instrument Co.

Radiation Counter Labs., Inc.

Tracerlab, Inc.

Victoreen Instrument Co.

Radioactive Isotopes

Abbott Laboratories

Atomic Energy of Canada, Ltd.

Bio-Rad Laboratories

Tracerlab, Inc.

Geiger Tubes

Amperex Electronic Corp.

Anton Electronic Labs.

Atomic Instrument Co.

Berkeley Div. of Beckman Instruments, Inc.

Curtiss-Wright Corp., Electronics Div.

Cyclotron Specialities Co.

Electronic Products Co.

El-Tronics, Inc.

General Electric Co.

Leighton Labs, H. W.

Nuclear Instrument & Chemical Corporation

Nucleonic Co. of America

Radiation Counter Labs., Inc.

Radiation Instrument Development Lab.

Radioactive Products, Inc.

Raytheon Mfg. Co.

Technical Associates

Tracerlab, Inc.

Victoreen Instrument Co.

Welch Allyn, Inc.

Western Radiation Lab.

Wood Counter Laboratory, N.

Scintillation Crystals

Harshaw Chemical Co.

Linde Air Products Co.

National Radiac, Inc.

Pilot Chemicals, Inc.

Tracerlab, Inc.

Isotope Developments Ltd.

Geiger Counters

Anton Electronic Labs., Inc.

Atomic Instrument Co.

Atomlab, Inc.

Beckman Instruments, Inc.

Berkeley Div. of Beckman Instruments, Inc.

Cam-Mac Division, Micro Specialities Co.

Curtiss-Wright Corp.

Detectolab, Inc.

Detectron Corp.

El-Tronics, Inc.

Fisher Research Laboratory, Inc.

Goldak Co.

Hoffman Laboratories, Inc.

Jordan Electronic Mfg. Co., Inc.

Menlo Research Laboratory

North American Philips Co.

Nuclear Instrument & Chemical Corporation

Nucleonic Co. of America

Precision Radiation Instruments, Incorporated

Radiation Counter Labs., Inc.

Radiation Instrument Development Lab.

Radioactive Products, Inc.

R-C Scientific Instrument Co.

Technical Associates

Tracerlab, Inc.

Victoreen Instrument Co.

Welch Allyn, Inc.

Western Radiation Lab.

Wood Counter Laboratory, N.

Young Sound Engineering Co., J. (Kits)

Scintillation Counters

Atomic Instrument Co.

Atomlab, Inc.

Berkeley Div. of Beckman Instruments, Inc.

El-Tronics, Inc.

Fisher Research Laboratory, Inc.

General Electric Co.

Goldak Co.

Macdonald Co., Inc., W. S.

National Radiac, Inc.

Nuclear Instrument & Chemical Corp.

Nucleonic Co. of America

Precision Radiation Instruments, Incorporated

R-C Scientific Instrument Co.

Sherwin Instrument Co.

Tracerlab, Inc.

Victoreen Instrument Co.

Stamco Instrument Corp.

Wood Counter Laboratory, N.

APPENDIX III

Abbreviations

A list of some of the abbreviations which may be encountered when dealing with atomic radiation. For definitions, see Appendix IV.

c - curie

cc - cubic centimeter

cm - centimeter

cm^2 - square centimeter

cpm - counts per minute

dps - disintegrations per second

ev - electron volt

g - gram

m - meter

MPC - maximum permissible concentration

MPE - maximum permissible exposure

r - roentgen

RBE - relative biological effectiveness

rd - rutherford

rem - roentgen equivalent man

rep - roentgen equivalent physical

r/hr - roentgens per hour

α - alpha

β - beta

γ - gamma

Prefixes

m - milli - (one thousandth, 10^{-3})

μ - micro- (one millionth, 10^{-6})

$\mu\mu$ - micromicro - (one trillionth, 10^{-12})

k - thousand (10^{3})

m - million (10^{6})

b - billion (10^{9})

For example, mc is the abbreviation for millicurie, μc for microcurie and $\mu\mu$c for micromicrocurie. krd is the abbreviation for kilorutherford, mev represents million electron volts, and bev is billion electron volts.

APPENDIX IV

Definitions

Working definitions of some of the terms commonly encountered when dealing with atomic radiation.

Alpha Rays – a stream of helium nuclei. The helium nucleus has a mass number of 4 and an atomic number of 2. It consists of two protons and two neutrons.

Anticoincidence – non-simultaneous occurrence of two or more events – usually refers to ionizing events.

Assay – an analysis to determine the relative radioactivity in an ore sample.

Atom – the smallest particle into which an element can be subdivided and still retain its chemical properties.

Atomic Battery – a battery which obtains its energy entirely from nuclear reactions.

Atomic Number – the characteristic of an element representing the net positive charge on the nucleus.

Atomic Radiation – radiation resulting from nuclear reactions. The most common forms of such radiation are alpha, beta, and gamma rays and neutrons.

Atomic Weight – the relative weight of the atom of an element compared to some standard. Usually the standard is oxygen with an atomic weight of 16.

Background Counts – counts caused by any agency other than the one which it is desired to detect.

Backscattering – reflection of incident radiation back towards the source.

Beta Rays – a stream of electrons.

Calorimeter — a device which measures the heat energy released in a reaction by measuring the temperature rise in a known quantity of water as a result of the reaction.

Chain Reaction — a nuclear reaction in which the energy in the products of a single disintegration is sufficient to produce more than one new disintegration, thus resulting in a cumulative effect.

Coincidence — occurence of two or more events simultaneously — usually refers to ionizing events.

Condenser r-Meter — a capacitor-ionization chamber combination requiring an auxiliary device for charging the capacitor.

Cosmic Rays — ionizing radiation entering the earth's atmosphere from outer space.

Count — an impulse generated by the detection of an ionizing event, resulting in a momentary aural or visual indication (click or flash).

Curie — a quantity of radioactive material which produces 3.700×10^{10} disintegrations per second.

Dead Time — the time immediately following a discharge when a detector is unable to respond to ionizing radiation.

Detector — a device for indicating the presence of ionizing radiation.

Deuterium — heavy hydrogen, or the isotope of hydrogen having a mass number of 2.

Dose — the total received quantity of ionizing radiation.

Dosimeter — an instrument or device for indicating the total dose of ionizing radiation.

Dynode — one of the intermediate electrodes in a photomultiplier tube.

Electrometer — an instrument for measuring small differences in electric potential between two points.

Electron — the elementary charge of negative electricity — one of the basic building blocks of matter

Electron Avalanche — a condition wherein the applied voltage is sufficient to accelerate ionized particles enough to produce further ionization.

Electron Volt — the amount of energy acquired by an electron when it moves through a potential difference of one volt.

Electroscope — an instrument for detecting the presence of an electric charge on a body; one type of electrometer.

Erg — a unit of energy equal to the work done when a force of one dyne acts through a distance of one centimeter. Ten million ergs per second equals one watt.

Film Badge — a badge containing a sensitized film which, when developed, indicates the total dose of ionizing radiation to which the badge has been subjected; one type of Dosimeter.

Fission — breaking up into parts. In atomic fission, the atom breaks up, producing a great deal of energy in the process.

Gamma Rays — electromagnetic radiation having an extremely short wavelength and great penetrating power. Wavelength is shorter than that of x-rays.

Gas Amplification — ratio of charge collected to charge produced by the original ionizing event.

Geiger Counter — a complete instrument for indicating or measuring atomic radiation in which the detecting portion is a Geiger tube.

Geiger Plateau — a range of voltages which result in relatively flat operating characteristics in a Geiger tube to which they are applied; fairly large changes in the applied voltage in this range result in only small changes in the output.

Geiger Tube — a two-electrode tube containing a small amount of gas which can be ionized by incident radiation. The normal shape is cylindrical, with a center conductor which is operated at a positive potential. The conducting cylinder is negative.

Half-Life — time required for the activity of a radioactive material to be reduced by half.

Halogen — a general name which applies to four chemical elements with some similar chemical properties. The elements are flourine, chlorine, bromine, and iodine.

Halogen Quenching — quenching the discharge in a counter tube by introducing a small quantity of one of the halogens (see quenching).

Heavy Water — water in which the hydrogen of the water molecule is in the form of the isotope deuterium.

Ion — an atom or molecule which has gained or lost one or more electrons and so has an electric charge.

Ionization — the process of adding or removing one or more electrons to or from an atom or molecule so that it becomes charged.

Isotope — variation of an element which has the same external electron configuration in the atom and so has the same chemical properties, but which has a different mass number

Mass Number — a number assigned to an atom which is equal to the sum of the protons and neutrons in the nucleus.

Meson — an elusive particle which may have a unit positive or negative charge or no charge at all, and may have any of a number of different weights. Life of the meson is very short.

Neutrino — a particle having the same mass as an electron but having no electrical charge.

Neutron — an elementary building block of matter having the same mass as a proton (hydrogen nucleus) but containing no charge.

Nuclear Accelerator — a device for accelerating nuclear particles such as electrons or protons.

Nuclear Reaction — a reaction in which the nucleus of an atom is disrupted or reorganized in some manner.

Nuclear Reactor — a device in which controlled nuclear reactions take place.

Phosphor — a material, such as zinc sulfide, which gives off visible light when struck by nuclear radiation. The inside face of a television picture tube is coated with a phosphor.

Photomultiplier Tube — a tube in which the electrons from a photo-emissive cathode are multiplied by secondary emission from a series of dynodes.

Photon — a unit bundle of electromagnetic energy.

Planchet — a small metal container or sample holder, usually used to hold radioactive materials which are being checked for the degree of radioactivity.

Positron — an atomic building block having the same mass as an electron but carrying a unit positive charge.

Proton — an elementary building particle carrying a unit positive charge and having a mass about 1840 times that of an electron. The nucleus of a normal hydrogen atom is a proton.

Prospecting — searching for radioactive material such as uranium or thorium.

Quenching — the process of preventing a continuous discharge in a counter tube which uses gas amplification.

Radiography — examination of materials such as heavy castings by means of gamma rays or high-energy x-rays.

Radioisotope — an isotope which is radioactive.

Radioactivity — spontaneous disruption of an atomic nucleus with the resultant emission of atomic radiation.

Radiophotoluminescence — a property of a material whereby its ability to give off visible light when irradiated with ultraviolet light depends on its previous exposure to nuclear radiation.

Ratemeter — an instrument for measuring the rate at which counts are received — usually in counts per minute.

Relative Biological Effectiveness (RBE) — a measure of the effectiveness of various types of radiation on human tissue. For example, alpha rays have an RBE of 20, indicating that they are 20 times as damaging as an equivalent dose of gamma rays.

Resolution — ability to separate counts which occur very close together in time.

Roentgen (r) — unit of quantity of radiation, defined as that quantity which will produce, in 0.001293 grams of air, ions carrying 1 electrostatic unit of electricity. This amount of air is equal to 1 cc at 0^oC and atmospheric pressure.

Roentgen Dose Meter — a meter for measuring the dose or quantity of radiation received by an object or person.

Roentgen Equivalent Man (rem) — relative effectiveness of radiation on the human body. By definition, 1 rem = 1 rep per RBE.

Roentgen Equivalent Physical (rep) — the quantity of radiation which produces energy absorption of 93 ergs per gram of tissue.

Rutherford (rd) — a quantity of radioactive material which will produce one million (10^6) disintegrations per second.

Saturation — condition in an ionization chamber when the applied voltage is sufficiently high to collect all the ions formed from the absorption of radiation, but insufficient to produce ionization by collision.

Scaler — device for indicating the total number of counts produced by a detector of some kind, such as a Geiger or scintillation counter.

Scintillation — flash of light produced in a phosphor or suitable crystal by ionizing radiation.

Self-Quenching — a counter tube which is quenched by means of a suitable component in the counting gas.

Survey — a critical examination of the radiation near a source.

Time-Constant — a measure of the time required for a capacitor to charge or discharge in a resistance-capacity circuit. It is numerically equal in seconds to the product of the resistance in megohms and capacity in microfarads.

Tracer — a radioactive material used to trace the progress of a reaction or process of some kind.

Tritium — a isotope of hydrogen having an atomic number of 3.

X-rays — electromagnetic rays having a wavelength between ultraviolet and gamma rays.

APPENDIX V

Bibliography

Here are some suggestions for those who would like to obtain more information on the general field of nuclear science. This bibliography is by no means intended to be comprehensive, but is merely representative of the type of material which is available.

Periodicals

"Atomic Energy Newsletter" — publishedbiweekly at 1000 Sixth Ave., New York, N. Y. Subscription price: $18.00 a year.

"Bulletin of the Atomic Scientists" — published monthly by Educational Foundation for Nuclear Science, Inc., 5734 University Ave., Chicago 37, Illinois, Subscription price: $5.00 a year.

"Nuclear Science Abstracts", issued twice monthly by the Atomic Energy Commission, Technical Information Service, Oak Ridge, Tenn. Subscription Price: $6.00 a year.

"Nucleonics" — a monthly periodical published by McGraw-Hill Publishing Company, 330 W. 42nd St., New York 36, N. Y. Subscription price: $8.00 a year.

Books

"Annual Review of Nuclear Science, Vols. 1, 2, and 3", edited by James G. Beckerley. Annual Reviews, Inc.

"Applied Atomic Energy" by K. Fearnside, E. W. Jones, and E. N. Shaw. Philosophical Library.

"Applied Atomic Power" by E. S. C. Smith and others, Prentice-Hall.

"Applied Nuclear Physics" by E. C. Pollard, and W. L. Davidson. Wiley.

"Atomic Energy", editedby J. L. Cramer and R. E. Peierls. Penguin Books.

"Atomic Energy", by Karl K. Darrow — Wiley.

"Atomic Experiments for Boys", by Raymond F. Yates — Harper.

"Atomic Power" by R. Barnard Way — Wells Gardner, Darton & Co.

"Business Opportunities in Atomic Energy", Atomic Industrial Forum 260 Madison Ave., New York 16, N. Y.

"Constructive Uses of Atomic Energy", edited by S. C. Rothmann — Harper.

"Electron and Nuclear Counters; Theory and Use", by S. A. Korff. — Van Nostrand.

"Elementary Nuclear Theory", by H. A. Bethe — Wiley.

"Elements of Nuclear Reactor Theory" by Samuel Glasstone and Milton C. Edlund — Van Nostrand.

"Explaining the Atom" by Selig Hecht — Viking.

"Foundations of Nuclear Physics" by Robert T. Beyer — Dover Publications.

"Fundamentals of Atomic Physics" by S. Dushman — McGraw-Hill.

"Industrial and Safety Problems of Nuclear Technology" by M. H. Shamos and S. G. Roth — Harper.

"Introduction to Nuclear Engineering", by R. L. Murray — Prentice Hall.

"Introduction to Nuclear Engineering", by Richard Stephenson — McGraw-Hill

"Introductory Nuclear Physics", by D. Halliday — Wiley.

"Ionization Chambers and Counters: Experimental Techniques" edited by B. Rossi and H. Staub — McGraw-Hill.

"Isotopic Tracers", by G. E. Francis, W. Mulligan, and A. Wormall — John deGraff, Inc.

"Meet the Atoms", by O. R. Frisch — Wyn.

"Nuclear Physics", by Alex E. S. Green — McGraw-Hill.

"Nuclear Radiation Physics", by R. E. Lapp and Howard L. Andrews — Prentice-Hall.

"Pocket Encyclopedia of Atomic Energy", by Frank Gaynor — Philosophical Library.

"Portrait of an Atom", by Lester delRey — Abelard Press.

"Radiation Biology", edited by Alexander Hollaender — McGraw-Hill.

"Radiation Monitoring in Atomic Defense", by Dwight E. Gray and John. H. Martens — Van Nostrand.

"Radioactivity and Nuclear Physics", by J. M. Cork — Van Nostrand.

"Radioisotopes; Industrial Application", by G. H. Guest — Sir Isaac Pitman and Sons, Ltd.

"Readings for the Atomic Age", edited by M. D. Hoffman — Globe Book Company.

"Scintillation Counters", by J. B. Birks — McGraw-Hill.

"Source Book on Atomic Energy", by Samuel Glasstone — Van Nostrand.

"The Atom At Work", by Jacob Sacks — Ronald Press.

"The Atomic Revolution", by Robert D. Potter — Robert M. McBride.

"The Atomic Story", by John W. Campbell — Henry Holt.

"The Elements of Nuclear Theory", by S. Glasstone and M. C. Edlund — Van Nostrand.

"Why Smash Atoms?", by A. K. Solomon — Harvard University Press.

"You and Atomic Energy and its Wonderful Uses", by John Lewellen — Children's Press.

"Young People's Book of Atomic Energy", by Robert D. Potter — Dodd, Mead.

Publications

The following list of publications can be obtained from the Office of Technical Services, Department of Commerce, Washington 25, D. C. at the price indicated.

"A Bibliography of Selected AEC Reports of Interest to Industry". (TID-3070, 7 parts) Complete set, $2.25. Chemistry & Chemical Engineering, 45¢; Construction & Civil Engineering, Mining & Geology, 25¢; Electronics & Electrical Engineering, 35¢; Health & Safety, Industrial Management, 25¢; Mechanics and Mechanical Engineering, 25¢; Metallurgy & Ceramics, 35¢; Nuclear Technology, 35¢.

"Atomic Control of Power Reactors" (AECD-3163) 20¢.

"A Thermal Neutron Survey Instrument" — 10¢.

"Bibliography of Particle Accelerators; July 1948 to December, 1950" (UCRL-1238) 25¢.

"Brookhaven Conference Report; High Speed Counters & Short Pulse Techniques" (AECU-26, NBL-C-1) 25¢.

"Completion Report on Improved Alpha Survey Instrument and Probe" — 20¢.

"Health Physics Insurance Seminar" (TID-388) 50¢.

"List of AEC Research Reports for Sale (list 23) — free.

"Machining Studies by Radiometric Methods" (PB111473) — 75¢.

"Nuclear Science in Engineering Education; a Selected List of References for Instructors" — 25¢.

"Radioactivity Measurement Techniques" (AECD-2270) — 15¢.

"Radioisotope Applications of Industrial Significance" — 30¢.

"Safe Handling of Radioactive Isotopes" (NBS Handbook 42) — 15¢.

"Scintillation Crystal Gamma Counter" — 35¢.

"Scintillation Detectors: A Selected List of Unclassified Reports" — 10¢.

"The Role of Engineering in Nuclear Energy Development" — $1.40.

"Unclassified Bibliographies of Interest to the Atomic Energy Program", 55¢.

The following publications can be obtained from Superintendent of Documents, Government Printing Office, Washington 25, D. C. at the price indicated.

"Civil Defense and Atomic Warfare — a Selected Reading List" (H-25-1) 25¢.

"Handling Radioactive Wastes in the Atomic Energy Program" — 15¢.

"Isotopes — A Five Year Summary of United States Distribution" $1.00.

"Maximum Permissible Amounts of Radioisotopes in the Human Body and Maximum Permissible Concentrations in Air and Water" (NBS Hand book 52) — 20¢.

"Measurements of Radioactivity" (NBS Circular 476) — 45¢.

"Nuclear Data" (NBS Circular 499); also supplements 1, 2, and 3.

"Prospecting for Uranium" — 55¢.

"Prospecting with a Counter" — 30¢.

"Radiological Monitoring Methods & Instruments" (NBS Handbook 51) — 15¢.

"Reports on the U. S. Atomic Energy Commission on Nuclear Power Reactor Technology" — 25¢.

"Selected Readings on Atomic Energy" — 15¢.

"Semiannual Reports of the U. S. Atomic Energy Commission to the Congress of the United States". First, 5¢; second, 10¢; third, 15¢; fourth (Recent Scientific and Technical Development in the Atomic Energy Program of the United States) 35¢; fifth (Atomic Energy Development, 1947-48) 45¢; sixth (Atomic Energy and the Life Sciences) 45¢; seventh (Atomic Energy and the Physical Sciences) 50¢; eighth (Control of Radiation Hazards in the Atomic Energy Program) 55¢; ninth (AEC Contract Policy and Operations) 40¢; tenth (Major Activities in the Atomic Energy Programs) 35¢; eleventh (Some Applications of Atomic Energy in Plant Science) 50¢; twelfth (Major Activities in the Atomic Energy Programs) 35¢; seventeenth (Major Activities in the Atomic Energy Programs) 45¢.

"The Effects of Atomic Weapons" (1950) $1.25.

"The Smyth Report" (1945) 40¢.

The following publications can be obtained from the United States Atomic Energy Commission, Technical Information Service. Oak Ridge, Tennessee, at the prices indicated.

"Design and Construction of Radiochemical Laboratories; A Selected List of Unclassified References" (TD-3013) 10¢.

"Nuclear Notes for Industry".

"Radioactive Waste Disposal: A Bibliography of Unclassified Literature" (TID-375) 10¢.

"Selected Unclassified Reference on Nuclear Reactors" (TID-3006)

"The First Pile" (TID-202) 10¢.

The following miscellaneous material may be obtained as indicated.

"A Business Man Asks — How Can I Keep Up With Atomic Energy Developments?" Industrial Information Branch, Atomic Energy Commission, Washington 25, D. C.

"An International Bibliography on Atomic Energy", United Nations, N. Y.(1949-1951) Vol. 1, 50¢; Vol. 1, Supplement no. 1, 25¢; Vol. 2, $10.

"Atomic Energy Reports to Executives", Reader Service Dep't., Business Week, 330 W. 42nd Street, New York 36, N. Y. 60¢.

"Business Opportunities in Atomic Energy", Atomic Industrial Forum, 260 Madison Ave., New York, N. Y. $6.00.

"Glossary of Terms in Nuclear Science and Technology" (Nine sections) American Society of Mechanical Engineers, 29 W. 39th St., New York 18, N. Y. (From 60¢ to $1.20 per section).

"Industrial Uses of Radioactive Fission Products", Project 361 Stanford Research Institute, Stanford, Calif. $1.50.

"Industry's Role in Atomic Energy." Nucleonics, McGraw-Hill Publishing Company, Inc., 330 W. 42nd St., New York 36, N. Y. 30¢.

"The New Atomic Energy Law — What it Means to Industry", Atomic Industrial Forum, 260 Madison Ave., New York, N. Y. $5.00.

Further information can be obtained from any of the various AEC offices throughout the country, or from the Atomic Industrial Forum, 260 Madison Avenue, New York, N. Y. There are a number of AEC depository libraries throughout the country where unclassified reports can be examined, including many reports which are not available for sale. A list of these libraries may be obtained from the United States Atomic Energy Commission, Technical Information Branch, Oak Ridge, Tenn. The AEC is very cooperative in making available any and all unclassified material dealing with its program.